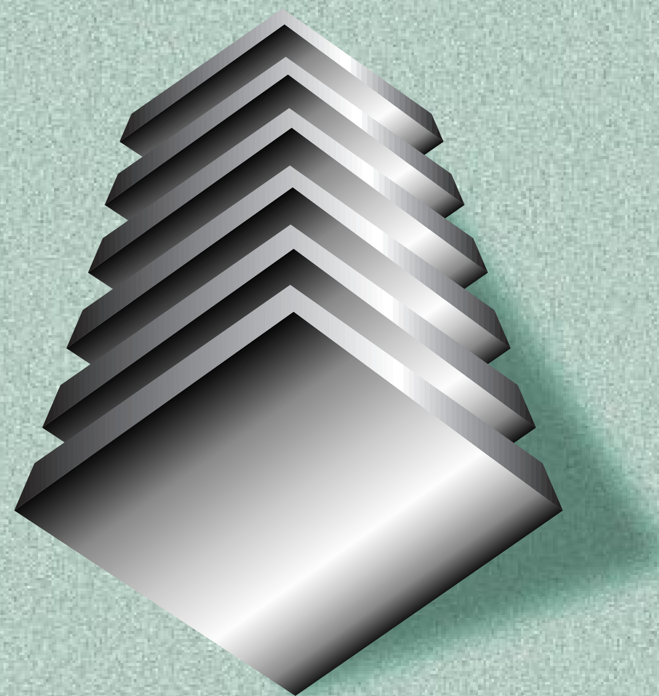
FUEL CELLS FOR TRANSPORTATION



2002
RESEARCH & DEVELOPMENT
PROGRAM ABSTRACTS

A C K N O W L E D G E M E N T

We would like to express our sincere appreciation to Argonne National Laboratory for its technical and artistic contributions in preparing and publishing this report.

In addition, we would like to thank all our program participants for their contributions to the programs and all the authors who prepared the project abstracts that comprise this report.

U.S. Department of Energy
Office of Advanced Automotive Technologies
1000 Independence Avenue, S.W.
Washington, D.C. 20585-0121

FY 2002

DOE Fuel Cells for Transportation Program: R&D Project Abstracts

Energy Efficiency and Renewable Energy
Office of Transportation Technologies

Approved by Steven Chalk **Energy Conversion Team Leader**

February 2002

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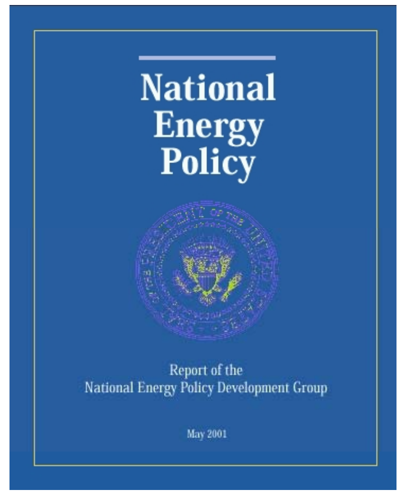
DOE Fuel Cells for Transportation Program: R&D Project Abstracts

INTRODUCTION

U.S. Commitment to the Development of Fuel Cell Technology

The commitment in the United States and around the world to the development of fuel cell technology for transportation applications remains very strong. In May 2001, the president's National Energy Policy Development Group published the National Energy Policy (NEP), which is a comprehensive energy policy that specifically recommends the development of energy-efficient vehicle technologies, including fuel cells, hybrid systems, and hydrogen-based systems. The U.S. Department of Energy (DOE) is committed to implementing this policy in a significant way by supporting research and development (R&D) activities that will lead to the private sector's development of highly efficient, low- or zero-emission fuel cell propulsion systems for automotive applications. The DOE program is conducted in cooperation with the Partnership for a New Generation of Vehicles (PNGV), a research and development partnership between the federal government and the U.S. Council for Automotive Research, which consists of Ford, General Motors, and Daimler-Chrysler. Since its inception, the Fuel Cells for Transportation Program has supported the PNGV through its technology research projects. The Partnership's goals are being reevaluated to identify changes that will maximize the potential national petroleum-savings benefit of the emerging advanced technologies. When these goal changes have been defined, the Office of Transportation Technologies (OTT) will adjust the focus of its technology research programs accordingly.



R&D Strategy – Overcoming the Most Critical Technical Barriers

The U.S. automotive and fuel cell companies continue to announce major breakthroughs in fuel cell technology, introduce new development vehicles, and form new partnerships. The DOE remains committed to contributing to this progress in a significant way by supporting R&D activities that address the most critical technical barriers to the introduction of commercially viable PEM fuel cell systems. This R&D program is implemented through cost-sharing cooperative agreements with automotive suppliers and fuel cell and component developers. Furthermore, DOE national laboratories and universities throughout the United States conduct R&D activities to increase the knowledge base and develop enabling technologies for PEM fuel cells. Although substantial progress has been made in advancing the technology, there is considerably more work to do to meet the technical targets that have been established for a fuel cell power system operating on EPA Tier 2 gasoline containing an average of 30 parts per million (ppm) sulfur. For more information on technical targets and progress, see the "FY 2001 Fuel Cells for Transportation Annual Progress Report."[1]

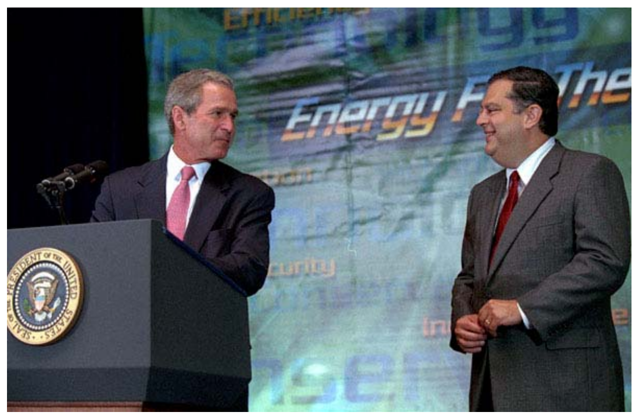
[1] http://www.ott.doe.gov

Remaining technical challenges for gasoline-fueled fuel cell power systems include:

- Reducing component and system costs
  - reducing precious metal requirements and
  - developing high-volume manufacturing capability,
- Demonstrating component and system durability,
- Reducing system start-up time,
- Developing high-efficiency air management subsystems, and
- Developing a suitable fuel infrastructure (sulfur-free gasoline and hydrogen).

Program Direction

During FY 2001, the DOE Fuel Cells for Transportation Program planned and executed an R&D solicitation that resulted in approximately $80 million (DOE share) in new research awards for more than 25 projects. On June 28, 2001, President Bush came to DOE and announced the awards by saying, "I'm pleased to announce … grants to encourage academia and the private sector to join with contributions from the [public] sector to accelerate the development of fuel cells, advanced engines, hydrogen technology and efficient appliances…." In addition to R&D of materials and components for PEM fuel cell stacks and on-board fuel processors, the awards include increased emphasis on on-board hydrogen storage and off-board hydrogen generation and refueling technologies, which are jointly supported with the DOE's Fuels for Fuel Cells Program and Hydrogen Program. With an average cost share of 28%, the total R&D value of the new projects is ~$115 million. Approximately 20 organizations, including two universities, received awards for projects that began in Fall 2001 and run between two and four years. The new awards were made for projects that address the most critical challenges to the commercialization of transportation fuel cell power systems.



President Bush with Secretary Abraham
during award announcement.

Remaining economic challenges include the capital costs of manufacturing fuel cells, cost of a new fuel infrastructure, and competition from other technologies.

New R&D projects selected from FY 2001 solicitation.

Project Descriptions	Challenges Addressed	Prime Contractor
Stack Components		
MEAs with High-Temperature Membranes and Higher-Activity Cathodes (4 awards)	Cost Pt Reduction Manufacturing	3M UTC Fuel Cells DeNora/DuPont Superior MicroPowders
Processes for Molding Bipolar Plates (1 award)	Cost Manufacturing	Porvair
Fuel Processing		
Catalysts/Materials/Components to Reduce Weight and Volume (3 awards)	Start-Up Time Cost	Nuvera U. Michigan Catalytica
Balance of Plant		
Compressor/Expander, Blowers, Heat Exchangers, Humidifiers (4 awards)	Air Management Balance of Plant Size Cost	UTC Fuel Cells Honeywell Arthur D. Little Mechanology
Chemical Species Sensors (2 awards)	Cost Durability/Reliability	UTC Fuel Cells Honeywell
Hydrogen Enhancement Technologies (2 awards)	Energy Efficiency Cost and Durability	UTRC U. Kentucky
Hydrogen Storage		
On-Board Hydrogen Storage (2 awards)	Fuel Infrastructure	UTRC SwRI
Hydrogen Refueling		
Hydrogen Refueling Technologies (3 awards)	Fuel Infrastructure	Air Products General Electric GTI
Assessments/Analyses		
Precious Metal Availability and Cost (1 award)	Platinum Cost/Supply	Arthur D. Little
Viability of Fuel Cell Auxiliary Power Units (1 award)	System Cost/Efficiency	Arthur D. Little
Energy, Emissions, and Cost Analyses of Fuels for Fuel Cells (1 award)	Fuel Infrastructure	Arthur D. Little
Fuel Cell Vehicle Codes and Standards and Recommended Practices (1 award)	Fuel Infrastructure	Society of Automotive Engineers
Small Stationary PEM Power Systems		
Ethanol-Fueled System (1 award)	Fuel Infrastructure	Caterpillar

In addition to the new contracts with industry, the DOE national laboratories will continue to provide valuable support to the Fuel Cells for Transportation Program. Through these efforts and other related projects, researchers in the Fuel Cells for Transportation Program will continue to improve cost, durability, efficiency, and overall system performance, allowing us to move closer to the commercial availability of fuel cell vehicles.

DOE national laboratory R&D in support of fuel cells for transportation program.

Laboratory	R&D Focus
Argonne National Laboratory	Systems Analysis Fast-Start Fuel Processing Fuels for Fuel Cells
Brookhaven National Laboratory	Low-Pt Electrodes
Jet Propulsion Laboratory	Platinum Deposition Techniques
Lawrence Berkeley National Laboratory	Electrocatalysis Electrodes
Lawrence Livermore National Laboratory	Sensors
Los Alamos National Laboratory	Improved Cathodes High-Temperature Membranes Durability Studies Fuels Effects
National Energy Technology Laboratory	Diesel Reforming
National Institute for Science and Technology	Neutron Imaging of Membrane Electrode Assemblies (MEAs) for Non-Destructive Evaluation
National Renewable Energy Laboratory	Fuel Cell Vehicle Modeling
Naval Research Laboratory	Non-Platinum Catalysts
Oak Ridge National Laboratory	Materials for Fuel Cells and Systems Bipolar Plates Membranes Systems Components
Pacific Northwest National Laboratory	Microchannel Fuel Processing

During the past year, cooperation with DOE's Hydrogen Program and Fuel Cells for Buildings Program was increased to maximize existing synergies. In May 2002, the Fuel Cells for Transportation Program and the Hydrogen Program will hold a joint R&D review for the first time. We also increased interactions with the Solid-state Energy Conversion Alliance (SECA), which is supported through the DOE Office of Fossil Energy, with a focus on fuel cells for auxiliary power to eliminate overnight idling in diesel trucks.

The Fuel Cells for Transportation Program will also support R&D on fuel cells for portable power. Portable power will likely be the first high-volume market for fuel cells because of their low power requirements and less-stringent cost target (~$5,000/kW). The manufacturing capability that develops for portable power fuel cells will help accelerate commercialization of fuel cells for transportation.

The remainder of this document presents abstracts of the R&D projects selected in the FY 2001 solicitation, as well as abstracts for ongoing industry and national laboratory R&D projects from previous solicitations. The abstracts provide an overview of the work being conducted to overcome the technical barriers associated with the development of fuel cell power systems. Each project abstract identifies the prime contractor, subcontractors (if any), major deliverables with expected delivery dates, and the name and phone number of the primary contact for obtaining additional project information. For more detailed information on DOE Office of Transportation Technologies activities supporting the development of PEM fuel cell technology, the reader is referred to the following FY 2001 annual progress reports:

Fuel Cells for Transportation FY 2001 Annual Progress Report
Fuels for Advanced CIDI Engines and Fuel Cells FY 2001 Annual Progress Report
Automotive Propulsion Materials FY 2001 Annual Progress Report
Snapshots of CARAT Projects, September 2001

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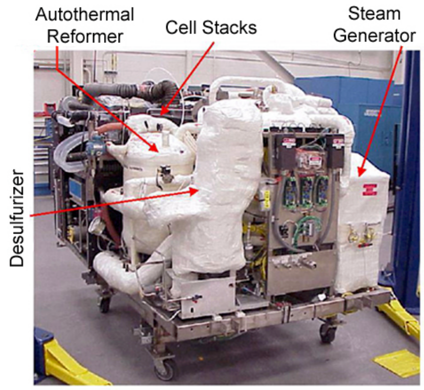
Fuel Cell Power System Development

Atmospheric Fuel Cell Power System for Transportation

Contractor: UTC Fuel Cells — *South Windsor, CT*
Contact: Murdo Smith — *(860) 727-2269*

UTC Fuel Cells has implemented an aggressive program to commercialize ambient-pressure polymer electrolyte membrane (PEM) fuel cell power plants for transportation applications. Although focused on gasoline operation, the power plant fuel processing system will utilize fuel-flexible reforming technology that can be modified to accommodate such fuels as methanol, ethanol, and natural gas. UTC Fuel Cells has tested a 50-kW_e gasoline fuel processing system and delivered a fully integrated, gasoline-fueled 50-kW PEM power plant to Argonne National Laboratory (ANL) for verification testing. Results of the power plant testing at UTC Fuel Cells include the following:



50-kW gasoline-fueled power plant.

- Rated power output (kW net) — 53
- Efficiency at 50 kW (%) — 22
- Efficiency at 12.5 kW (%) — 32
- Specific power (kW/kg) — 0.08
- Power density (kW/L) — 0.07
- Operating voltage range (V) — 225–420
- Fuel — California RFG II

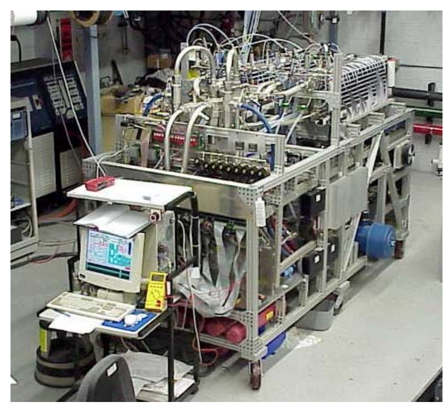
The follow-on phase of the program includes delivery of a fully integrated, gasoline-fueled 75-kW advanced PEM power plant.

<u>Deliverable</u>: *75-kW PEM power plant to ANL (11/02).*

Pressurized Fuel Cell Power System for Transportation

Contractor: Plug Power, Inc. — *Latham, NY*
Contact: William Ernst — *(518) 782-7700*

The purpose of this program has been to develop, demonstrate, and deliver a 50-kW_e (net) integrated fuel cell power system for automotive applications that can use gasoline, methanol, ethanol, or natural gas. We developed the fuel cell subsystem, and Nuvera Fuel Cells developed the fuel processor subsystem. The work began in October 1997 and was completed in three phases: Phase I (overall system definition, preliminary component development, and demonstration of a 10-kW_e brassboard integrated system), Phase II (development of the fuel cell stack, the fuel processor, auxiliary components, control strategy, and hardware for a 50-kW_e system), and Phase III (assembly and development testing of a 50-kW_e brassboard system using the Phase II components). The program concluded with the demonstration of the integrated, combined operation of the Phase III fuel cell and fuel processor subsystems in January 2001. The system was successfully operated on gasoline up to a gross power output of 35 kW_e, which was limited only by the use of one-half of the designed fuel cell stack size and operational limitations associated with tail gas combustor/CMEU (compresser/motor/expander unit) integration. The fuel processor supplied reformate with an H_2 concentration very close to the projected level of 40%, and CO concentrations were generally below 50 ppm.

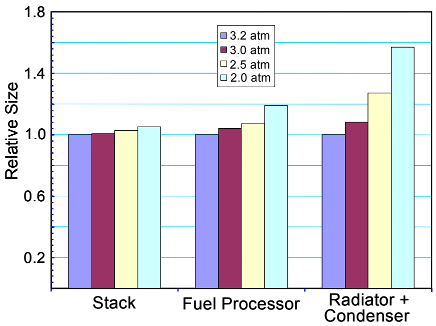

Phase III brassboard fuel cell subsystem.

<u>Subcontractor</u>:
Nuvera Fuel Cells (formerly Arthur D. Little Epyx), Cambridge, MA

<u>Deliverables</u>: *35-kW_e stack to DOE for testing (02/01); final report on evaluation of 50-kW integrated fuel cell power system performance (07/01).*

Fuel Cell Systems Design and Analysis

Contractor: Argonne National Laboratory — *Argonne, IL*
Contact: Romesh Kumar — *(630) 252-4342*



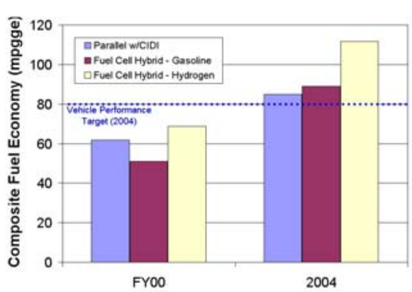
Effect of operating pressure on component sizes for a pressurized gasoline-fueled automotive fuel cell system.

We have developed a comprehensive system modeling capability for the design and analysis of automotive fuel cell systems. The simulations are carried out by using GCtool, a systems analysis software package that is available for licensing. Our work is addressing the influence of design, operating parameters, and system configuration on system efficiency, transient response, and cost. These analyses help identify the key improvements needed in component performance and the potential trade-offs in efficiency, cost, and power density to meet automotive requirements. For example, our analyses have quantified the effects of operating pressure on the relative sizes of the fuel cell stack, the fuel processor, and the radiator and condenser for a pressurized polymer electrolyte membrane (PEM) fuel cell system. The analyses show that decreasing the operating pressure from 3.2 to 2.0 atm would increase the sizes of all components; for example, the fuel cell active area would increase by ~5%, fuel processor volume would increase by ~20%, and the radiator and condenser masses would increase by ~60%. We have also analyzed atmospheric pressure systems, in which waste heat rejection and water management are significant issues. In addition, we are working with Arthur D. Little to define system configurations, environmental parameters, and component performances for their manufacturing costs studies and to evaluate trade-offs in size, cost, and efficiency.

<u>*Deliverables*</u>**:** *Workshops and reports on system integration and trade-offs needed to develop compact, efficient, and cost-effective fuel cell systems.*

Fuel Cell Vehicle Systems Analysis[2]

Contractor: National Renewable Energy Laboratory — *Golden, CO*
Contact: Keith Wipke — *(303) 275-4451*



Our focus is to evaluate current component technologies and future concepts from a vehicle systems perspective. ADVISOR and PSAT are two vehicle-systems-modeling tools used to understand the impacts of component characteristics on vehicle attributes. In the past year, we have applied these tools to various analytical studies. One study showed that 80 miles per gallon gasoline equivalent (mpgge) for a family sedan seems to be technically feasible by using the component-level technical targets specified by OAAT, but cost goals may be exceeded. In another study, we determined that a fuel-cell-powered mid-size sport utility vehicle could achieve ~56 mpgge. Current models for vehicle and fuel cell systems are being improved on the basis of experimental data. New component models, including detailed dynamic models based on GCtool, are under development. National Renewable Energy Laboratory staff provide guidance to the technical teams using these tools during the technical target-setting process. This effort is guiding future research by linking optimization tools with robust models of vehicle systems.

<u>*Deliverable*</u>: *Project performance of a DOE-technology-based fuel cell vehicle (05/02).*

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[2] This project was funded by the Vehicle Systems Program of OAAT.

Cost Analyses of Fuel Cell Stacks/Systems

Contractor: Arthur D. Little, Inc. *Cambridge, MA*
Contact: Eric J. Carlson *(617) 498-5903*

The performance and cost of polymer electrolyte membrane fuel cell (PEMFC) systems are critical to the successful commercialization of transportation fuel cell technology. The power density, efficiency, emissions, fuel flexibility, and cost of fuel cell systems relative to other power-train technologies will determine their market success. In this program, a fuel cell system model (reformer/fuel cell) was developed in conjunction with Argonne National Laboratory to define the system configuration and size of the components. This system configuration then served as the basis for the development of a bottom-up activity-based cost model for the manufacture of fuel cell systems at high production volumes. During this multiyear project, we have developed a baseline model for year 2000/2001 technology, solicited feedback from the fuel cell industry on the model's validity, considered the impact of operating parameters and various technology developments on cost, and assessed the potential long-term cost of reformate and direct hydrogen systems. The results of these analyses have assisted DOE in (1) the development of research priorities and long-term cost goals and (2) the assessment of proposed technology scenarios for fuel cell systems.

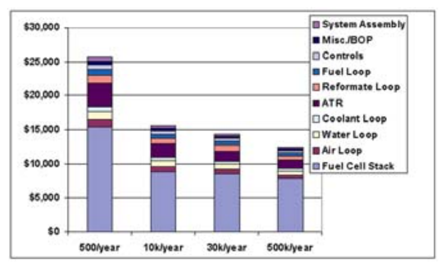
	Factory Cost Estimate		
Subsystem	**2001 Baseline ($/kW)**	**High Power ($/kW)**	**Change (%)**
Fuel Cell	237	153	-35
Fuel Processor	77	85	11
BOP	10	11	10
System Assembly	13	14	4
Total	**337**	**264**	**-22**

<u>Deliverables</u>: *Baseline cost model and polymer electrolyte membrane system technology synopsis, potential opportunities for cost reduction, assessment of cost impact of technology scenarios, and cost projection updates on annual basis (9/02).*

DFMA Cost Estimates of Fuel-Cell/Reformer Systems at Low, Medium, and High Production Rates

Contractor: Directed Technologies, Inc. *Arlington, VA*
Contact: Brian D. James *(703) 243-3383*

To assess the competitiveness of fuel-cell-powered vehicles, we have conducted detailed cost estimates of a complete fuel-cell system at several annual production rates. Such cost estimates will identify remaining areas of high cost and help assess the potential of fuel cell systems. This past year, we established a baseline system design that included the fuel tankage and delivery system; the autothermal reformer; a preferential oxidation gas cleanup unit; a polymer electrolyte membrane (PEM) fuel cell stack system; and all the necessary control, electrical, and safety systems. DFMA[3] techniques were applied to estimate the material, manufacturing, and assembly costs at annual production rates of 500, 10,000, 30,000, and 500,000 units and to suggest alternative design choices that might lower total cost. Total cost varied from \$520/kW at 500 units/year to \$250/kW at 500,000 units/year. The most expensive component was the fuel cell stack because of the high cost of platinum catalyst, the low power density operating point selected to boost overall system efficiency (0.7 V/cell at 400 mA/cm^2 to yield 280 mW/cm^2), and the high cost of membrane ionomer. Changes in the operating point of the fuel cell stack (i.e., operation at 0.6 V/cell) can reduce system cost significantly, but they would also lower system efficiency.



Cost estimates for 50-kW$_{net}$ power system.

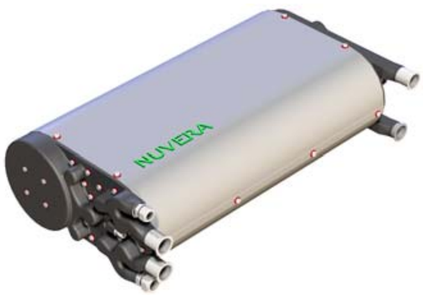
<u>Deliverables</u>: *Detailed power system cost estimates (11/01, 11/02, 11/03) and in-depth trade-off studies (05/02, 11/02, 05/03, 11/03).*

[3] DFMA is a registered trademark of Boothroyd Dewhurst, Inc.

Fuel Processing Subsystem

Advanced Fuel Processor Development for Transportation Fuel Cell Power Systems

Contractor: Nuvera Fuel Cells, Inc. *Cambridge, MA*
Contact: Prashant S. Chintawar *(617) 498-6577*



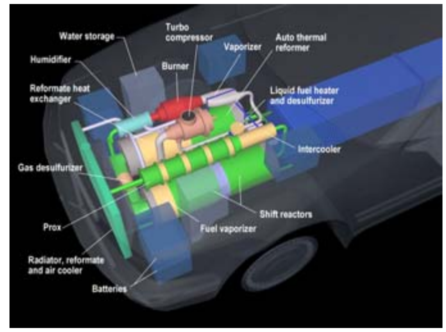
Widespread implementation of fuel cell power systems for transportation markets requires significant improvements in fuel processor technology. At the onset of our R&D program, we performed automotive system analyses to set performance and cost targets for key components (catalysts, adsorbents, heat exchangers, substrates, cleanup media) and to identify system-level strategies for weight and volume reduction of the fuel cell power system. The current focus is on integrating these key components in a compact fuel processor that not only meets the PNGV targets, but also has the shape factor for packaging in light-duty vehicles. Our first design containing advanced components was a natural gas fuel processor with a power density of 1.2 kW/L H_2. This unit is being tested now, and preliminary data indicate an efficiency exceeding 80% over a wide operating regime. On the basis of these results, we have designed a Substrate-based Transportation application Autothermal Reformer (STAR) — a multi-fuel processor that contains a compact and highly efficient (>95% removal efficiency) gasoline desulfurizer. Our computational fluid dynamics (CFD) and theoretical analyses of STAR suggest full-power hydrogen efficiency of >80% on California Phase II gasoline and a power density of 2.3 kW/L H_2. With the extensive use of structured automotive-application-specific media, our new-generation STAR fuel processor can be mounted vertically or horizontally. By using advanced sulfur-removal technology, gasoline can be used effectively as a fuel for automotive fuel cell power systems.

To further improve our fuel cell technology, we will undertake an R&D program leading to the design, fabrication, demonstration, and delivery of an advanced High-efficiency, Quick-start (HiQ) transportation fuel processor. This next-generation system addresses two of the most essential criteria for the commercialization of fuel cell power systems for vehicles: the need for high net system efficiencies and rapid start-up times (<30 s). These goals will be achieved by optimizing our existing catalytic fuel processing technology and developing a new system architecture. This new configuration will improve net system efficiency and provide nearly instantaneous power availability (<10 s) through integration and elimination of fuel cell and fuel processor balance-of-plant components. By using the same hardware as that used in conventional polymer electrolyte membrane (PEM) fuel cell systems, we expect a net improvement in efficiency of 10–15%. As a part of this program, Nuvera will work closely with a consortium of world-class industrial and academic partners.

Deliverables: *Demonstration of STAR Phase I power system at $\geq$ 50 kW$_e$ level (01/02), delivery of STAR Phase II fuel processor system (07/03), proof-of-concept verification (05/03), and demonstration and delivery of HiQ fuel processor to DOE (09/05).*

Multi-Fuel Processor for Fuel Cell Vehicle Applications

Contractor: McDermott Technology, Inc. — *Alliance, OH*
Contact: Thomas J. Flynn — *(330) 829-7622*



The team of McDermott Technology, Catalytica Energy Systems, and NexTech Materials will design, build, and demonstrate a fully integrated, 50-kW_e catalytic autothermal fuel processing system. The system will produce a hydrogen-rich gas for use in polymer electrolyte membrane (PEM) fuel cell systems for vehicle applications. The processor will consist of a liquid-phase desulfurizer, an autothermal reformer with a bifunctional catalyst, two water-gas-shift catalytic reactors, a selective oxidation unit (provided by Los Alamos National Laboratory [LANL]), and a microchannel steam generator (provided by Pacific Northwest National Laboratory [PNNL]). Rockwell Automation will supply a PLC-based control system. All catalyst formulations used in the system are compatible with monolith supports. Predicted fuel processor efficiency is ≥80% at 25% load, compared with the U.S. Department of Energy (DOE) target of 80%. During 2001, we completed the mechanical and electrical design for the fuel processor assembly and began fabrication and assembly of the skid-mounted fuel processor system. Catalytica Energy Systems supplied its newly developed bifunctional autothermal catalyst to McDermott Technology for incorporation into the autothermal reformer reactor. NexTech Materials supplied its platinum ceria water-gas-shift catalyst. Demonstration testing is scheduled for the first quarter of 2002.

Subcontractors:
Catalytica Energy Systems, Inc., Mountain View, CA
NexTech Materials, Ltd., Columbus, OH

Deliverable: *50-kW_e fully integrated fuel processor (04/02).*

Integrated Fuel Processor Development

Contractor: Argonne National Laboratory — *Argonne, IL*
Contact: Shabbir Ahmed — *(630) 252-4553*

Without a hydrogen-refueling infrastructure, fuel cell vehicles will require on-board fuel processors to convert available fuels into hydrogen. This conversion involves numerous unit processes and operations so that the reformate can meet the specifications of the polymer electrolyte membrane (PEM) fuel cell. Units designed for the fuel cell vehicle should be compact, lightweight, and energy-efficient. We have designed a fuel processor that integrates the reformer, sulfur trap, and water-gas-shift reactor with the required unit operations (air preheating, steam generation, etc.) inside a single vessel. The reformer section uses microchannel monoliths and pellets of reforming catalysts developed and patented by Argonne. The sulfur trap consists of commercially available ZnO pellets. The shift-reaction zone is packed with nonpyrophoric catalysts, which were also developed at Argonne.

The 12-L fuel processor is designed to generate up to 150 L/min of hydrogen (10 kW_e equivalent). We anticipate light-duty vehicles to be designed for 40–60 kW_e of peak power. Experiments have shown that gasoline containing ~30 ppm sulfur can be converted to a reformate stream containing ≥40% H_2 and ~1% CO. The energy efficiency of the conversion process is 78%. Rapid-start capability is a key requirement for automotive fuel cell systems. Our R&D effort is directed toward the design and demonstration of fast-start fuel processors.

Deliverable: *Demonstrate fuel processor 5-minute start-up time (09/02).*

Microchannel Fuel Processing

Contractor: Pacific Northwest National Laboratory *Richland, WA*
Contact: Larry Pederson *(509) 375-2731*

Engineered microchannels offer advantages in heat and mass transfer that help in the development of a compact, integrated, and energy-efficient hydrocarbon fuel processing system based on steam reformation. Consisting of reactors, recuperative heat exchangers, fuel and water vaporizers, combustors, and separators, the fuel processing system achieves high efficiency through meticulous heat management. Steam reforming is endothermic, and so it can make effective use of heat from the catalyzed combustion of unutilized hydrogen and methane in the fuel cell anode exhaust. The hydrogen content in the reformate stream is higher than that obtained from partial oxidation or autothermal reforming because the reformate is not diluted with nitrogen from air. Operating on isooctane, the steam-reforming system has achieved a capacity greater than 20 kW_e, a power density greater than 3,400 W_e/L, and a specific power greater than 600 W_e/kg.

<u>Deliverables</u>: *Demonstrate fuel flexibility of the steam-reforming system with gasoline, methanol, ethanol, propane, butane, and methane (01/02); demonstrate high- and low-temperature water-gas shift in a microchannel reactor (03/02); demonstrate a one-fifth-scale water vapor-liquid separator to recover moisture from a simulated cathode stream (04/02); and demonstrate steam-reforming catalyst lifetimes >1,000 h by using benchmark gasoline (09/02).*

Reformate Fuel Cell System Durability

Contractor: Los Alamos National Laboratory *Los Alamos, NM*
Contact: Rod Borup *(505) 667-2823*

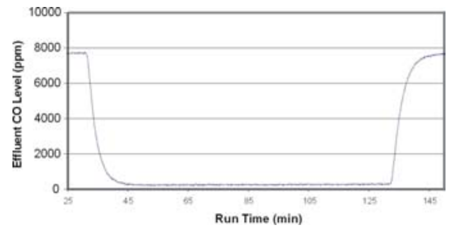
We are exploring effects of fuel constituents and fuel impurities on the durability of the fuel cell system to support the DOE's target of 5,000 h of operation. To measure durability, we have assembled a modular fuel processor incorporating modules for partial oxidation, isothermal high- and low-temperature shift, and preferential oxidation. The design permits each subsection to be controlled independently so that current or newly developed catalysts can be operated at their optimal conditions. The fuel processor produces reformate for a small fuel-cell stack (up to 2 kW_e) or multiple single cells. Initial tests of stack component durability will be undertaken with 50-cm^2 single cells. During testing, we will continuously monitor voltage/current performance of the stack, generate periodic polarization curves, measure AC impedance to characterize membrane resistivity, and measure hydrogen adsorption/desorption to monitor the surface of the anode catalyst surface. Post-characterization of stack components (specifically, membrane electrode assemblies [MEAs]) will involve conducting elemental analysis, determining catalyst particle size, and taking microscopic cross-sections. Low-level analyses for reformate impurities are conducted to determine if potential MEA-poisoning species are present. This task is critical because the reduction in fuel cell catalyst loadings to meet DOE cost targets makes the catalyst more susceptible to poisoning. The concentration level for total saturation of the anode catalyst at 5,000 h of operation is calculated to be 10 ppb. To adequately understand the effects of reformate on durability, we will further develop the analysis of reformate gas to measure potential poisoning species to that concentration.

<u>Deliverable</u>: *1,000 h total single-cell operation on reformate (06/02).*

R&D of a Novel Breadboard Device Suitable for Carbon Monoxide Remediation in an Automotive PEM Fuel Cell Power Plant

Contractor: Honeywell Engines and Systems *Torrance, CA*
Contact: Stan Simpson *(310) 512-4804*

Low CO concentrations in reformate are practically unavoidable, even with state-of-the-art reforming technology. The goal of our program is to develop and demonstrate a novel CO-removal system that provides high removal efficiency, low parasitic hydrogen consumption, and tolerance to variations in CO input concentration in an easily controlled manner. Two innovative approaches to selective CO removal and regeneration have been investigated: adsorption/catalytic oxidation (ACO) and electrocatalytic oxidation (ECO). Both make use of multiple CO-selective adsorption surfaces that can be regenerated quickly and efficiently with minimum hydrogen consumption. The two methods differ in the manner by which the active adsorption surfaces are regenerated. In ACO, CO is adsorbed over a bifunctional material and subsequently oxidized chemically to CO_2. In ECO, the adsorbed CO is removed via electrocatalytic oxidation. On the basis of a critical evaluation of the performance, efficiency, and cost of the two technologies, ECO was selected for further scale-up and testing. A breadboard device will be designed, fabricated, and tested that has the capability to remove 5,000 ppm CO from a reformate stream, consistent with the operation of a 10-kW polymer electrolyte membrane (PEM) fuel cell stack.



Demonstration of continuous CO removal (8,000 ppm CO) from reformate using a laboratory-scale ECO cell.

Deliverable: *CO-removal unit for a 10-kW PEM fuel cell stack (12/01).*

Reformate Cleanup Development

Contractor: Los Alamos National Laboratory *Los Alamos, NM*
Contact: Michael Inbody *(505) 665-7853*

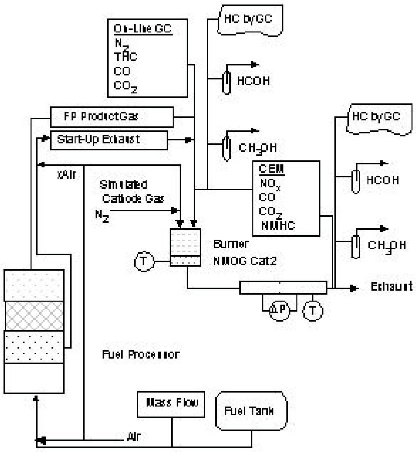
Reformate cleanup is necessary to remove potential contaminants to levels that do not compromise fuel cell performance. Ongoing R&D has resulted in the development of preferential oxidation (PrOx) reactors that have demonstrated removal of CO to <10 ppm from an inlet concentration of 2% CO in gasoline reformate. We are collaborating with fuel processor developers to adapt PrOx technology into their systems. We are working with McDermott Technology to supply it with a PrOx reactor system and with Argonne National Laboratory to develop a PrOx design for integration with its fuel processor.

Catalyst investigations are focused on improving PrOx reactor performance to reduce reactor size, reduce pressure drop, and increase reactor durability. A study will be conducted with PrOx catalysts on monoliths, as well as on ceramic and metal foams, to quantify advantages and disadvantages of each type of substrate. We are also addressing the key technical barrier of PrOx transient response to power transients and CO concentration transients. Control of step transients over a 1:3 flow range was demonstrated on a 1-s time scale. We are adding the capability to measure transients at faster time scales (≤100 ms). In a simulated start-up transient, a laboratory PrOx system reduced an inlet 5% CO in gasoline reformate to an outlet value of less than 10 ppm in 225 s. The 2008 technical target is less than 60 s; thus, further improvement is needed.

Deliverable: *Delivery of laboratory PrOx reactor test system to McDermott Technology (12/01).*

Evaluation of Partial Oxidation Fuel Cell Reformer Emissions

Contractor: Arthur D. Little, Inc. *Cupertino, CA*
Contact: Stefan Unnasch *(408) 517-1563*



In this project, emissions from a gasoline fuel processor and integrated fuel cell system will be characterized. Fuel cell vehicles can operate on gasoline when equipped with a fuel processor that converts gasoline to hydrogen, which is consumed in the fuel cell stack. The stack exit gas stream, which contains some hydrogen, traces of hydrocarbons (HC), and methane, is combusted in a burner. Emissions will be measured before and after the anode gas burner to quantify the effectiveness of the burner catalyst in controlling emissions at steady state and during transients. The emissions sampling system includes continuous emissions monitors for O_2, CO_2, CO, NO_x, and total HC. HC speciation analysis will be performed via gas chromatography. This analysis will yield the concentrations of the hydrocarbon species required for the California non-methane HC calculations. Particulate concentrations in the anode burner exhaust will be measured by using a filter in the exhaust stream.

A preliminary test of a Nuvera fuel processor was completed in September 2000. A UTC Fuel Cells integrated fuel cell and fuel processor will be tested in early 2002. A subsequent test of an integrated Nuvera fuel cell and fuel processor is also planned for early 2002.

Subcontractors:
Nuvera Corporation, Cambridge, MA
Air Toxics, Ltd., Sacramento, CA
Clean Air Vehicle Technology Center, Hayward, CA

Deliverable: *Final emissions report (06/02).*

Catalytic Autothermal Reforming

Contractor: Argonne National Laboratory *Argonne, IL*
Contact: Michael Krumpelt *(630) 252-8520*

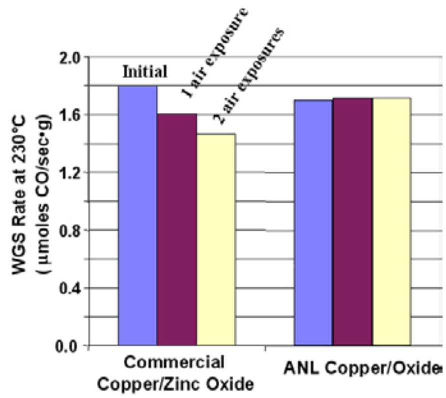
The market acceptance of fuel cell vehicles will depend largely on the ability to operate these vehicles on fuels available through the refueling infrastructure. On-board fuel processors will have to convert these fuels to produce H_2 fuel for the polymer electrolyte membrane (PEM) fuel cell. We have developed a novel material consisting of an oxide-ion conducting substrate and a group VIII metal that catalyzes the reaction between the hydrocarbons present in gasoline with air and steam to produce H_2 and carbon oxides. These materials catalyze the desired reforming reactions at ~700°C and low steam-to-carbon ratios (1–1.5). Experiments have shown the kinetics of these reforming reactions are quite fast. The resulting product also yields a higher selectivity for H_2 and CO_2, with the level of CO being commensurately low. Long-term tests with gasoline fuels have also shown that some formulations are tolerant of the sulfur present in such fuels as gasoline. We have developed a microchannel form of the catalyst that allows reforming at very high space velocities, making it possible to anticipate an automotive reforming reactor as small as a coffee cup (500 mL).

We have signed a licensing agreement with Sud-Chemie (formerly United Catalyst), which will manufacture and distribute the new catalyst. In recognition of this catalyst, we received an R&D 100 Award for 2001 from *R&D Magazine*.

Deliverable: *Sulfur-tolerant, non-noble metal reforming catalysts (09/02).*

Alternative WGS Catalyst Development

Contractor: Argonne National Laboratory (ANL) — *Argonne, IL*
Contact: Deborah Myers — *(630) 252-4261*



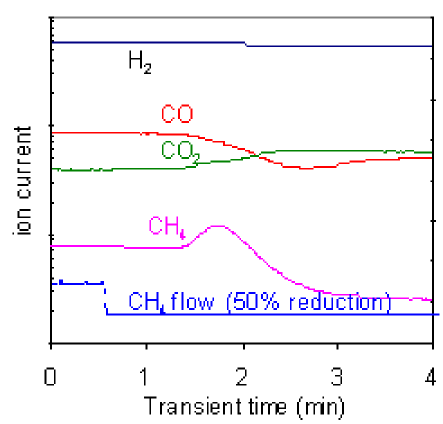
The H_2-rich reformate from the reforming of a hydrocarbon fuel may contain as much as 10% CO, which has been shown to reduce the power output of a polymer electrolyte membrane (PEM) fuel cell at concentrations as low as 10 ppm. The water-gas-shift (WGS) reaction is used to convert the bulk of CO in the reformate to CO_2 and additional H_2. Because of its intermittent duty cycle and size/weight constraints, the automotive application requires WGS catalysts that eliminate the need to sequester the catalyst during system shutdown, eliminate the need to activate the catalyst *in situ*, increase tolerance to temperature excursions, and reduce the size and weight of the shift reactors. We have developed a copper/oxide catalyst that has activity comparable with that of commercial copper/zinc oxide and higher than that of commercial iron-chrome. Our copper/oxide catalyst, unlike commercial catalysts, is active over the entire WGS temperature regime and does not lose activity after exposure to air or water. Our estimates show that this catalyst has the potential to reduce the WGS catalyst volume to 13% of the commercial catalysts. We have also developed an air-stable cobalt catalyst with higher activity than commercial iron-chrome. We demonstrated that reactors based on Argonne's cobalt and copper catalyst powders reduced the carbon monoxide level in simulated reformate from 10.4% to <1%. Efforts are under way to fabricate these catalysts in structured forms that are more suitable for the automotive application (e.g., monoliths).

<u>Deliverable</u>: *Demonstrate a water-gas-shift reactor with an outlet of <1% CO by using a structured nonprecious metal catalyst (06/02).*

Plate-Based Fuel Processing System

Contractor: Catalytica Energy Systems, Inc. — *Mountain View, CA*
Contact: Brian Engleman — *(650) 940-6391*

Catalytica Energy Systems, Inc., (CESI) is developing fuel reforming and fuel processing technology for use with automotive polymer electrolyte membrane (PEM) fuel cells. This technology is based on CESI's proprietary *Xonon*™ Cool Combustion technology that is applied commercially in ultra-low-emissions gas turbines. CESI has developed a methane steam reformer that integrates the catalytic reformer with catalytic combustion to provide a reformer package that has high efficiency, low volume, and low weight. The methane-fueled reformer reactor, sized to 50 kW(e), would achieve 6 kW/L and 2 kW/kg. A subscale unit has shown very good catalyst durability and good transient capability, as shown in the figure. CESI plans to apply this technology to a steam-reformer-based, gasoline-fueled fuel-processing system to produce PEMFC-quality hydrogen. In Phase 1, CESI will concentrate on the design and testing of the major components, including sulfur removal, the gasoline reformer, water gas shift, and preferential CO oxidation. In Phase 2, CESI will build a breadboard 2-kW(e) fuel processing system and demonstrate major performance objectives. In Phase 3, CESI will build a stand-alone 50-kW(e) fuel processing system for delivery to DOE. Weight and volume targets for the 50-kW(e) system are < 200 kg and < 200 L. An important aspect of the program will be the design of innovative reactor configurations that drive (1) reduced size, reduced weight, and fast transient capability and (2) the development of catalyst materials that integrate well with these configurations.

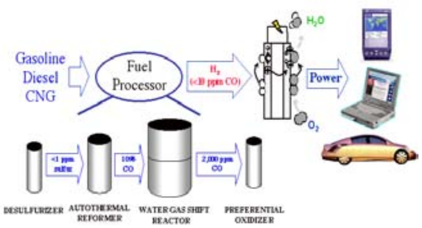


Transient response demonstration on 1-kW(e) methane steam reformer unit.

<u>Deliverable</u>: *50-kW plate-based fuel processing system (09/05).*

Microsystem-Based Fuel Processors for PEM Fuel Cells

Contractor: The University of Michigan *Ann Arbor, MI*
Contact: Professor Levi Thompson *(734) 936-2015*



The goal of this project is to produce prototype fuel processors to support polymer electrolyte membrane (PEM) fuel cells rated up to 25 kW_e. Significant improvements over the present technology will be achieved by coupling low-cost microchannel systems, high-performance shift and preferential oxidation catalysts, and high-efficiency microcombustors being developed at the University of Michigan (UM). The microchannel system will allow (1) more efficient thermal integration of the fuel processor components and elimination of conventional heat exchangers, (2) optimization of temperature profiles and minimization of the catalyst bed sizes, and (3) better cold-start and transient responses. The project goal will be accomplished in five major phases. Phase 0 comprises reassessment of the state of the art and, as necessary, refinement of size-reduction strategies. In Phase 1, design relationships for the individual fuel processor components will be determined. These relationships will be used in Phase 2 to design and construct individual microchannel-based fuel processor components capable of supporting a 1-kW fuel cell. The components will be third-party tested (Phase 3) and will provide the basis for design and fabrication of larger gasoline fuel processors during the final phase (Phase 4). The microchannel systems will be fabricated by using novel micro-drilling and micro-machining methods developed at UM.

<u>Subcontractors</u>:
Hydrogen Burner Technology, Inc., Rancho Dominguez, CA
MesoSystems Technology, Inc., Richland, WA
Ricardo, Inc., Belleville, MI

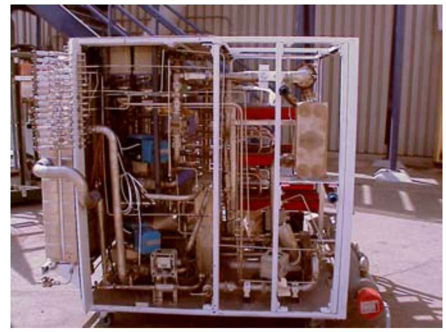
<u>Deliverables</u>: *1-kW_e gasoline fuel processor (11/04) and*
25-kW_e gasoline fuel processors (11/05).

Fuel Cell Stack Subsystem

High-Efficiency, High-Power-Density, CO-Tolerant PEM Fuel Cell Stack System

Contractor: Honeywell Engines and Systems *Torrance, CA*
Contact: Tim Rehg *(310) 512-2281*

The polymer electrolyte membrane (PEM) fuel cell power plant is potentially a cleaner, more efficient alternative to the automobile internal combustion engine (ICE). To warrant consumer acceptance, however, performance, cost, and utility must be comparable with that of today's vehicles. We are developing a 50-kW (net) PEM fuel cell power system that can operate on reformed hydrogen derived from such fuels as gasoline and methanol. The system will be highly fuel-efficient, compact and lightweight, and cost-effective (high-volume production is estimated to cost \$100/kW). In FY 2001, we initiated the design and construction of the 50-kW brassboard system, incorporating its third stack design and molded composite bipolar plates. We project system fuel efficiency to be 45% at 12.5 kW and system power densities to be ~0.2 kW/kg and ~0.15 kW/L. The above numbers include contributions from off-the-shelf components (i.e., oversized valves and heat exchangers). Using components specifically designed for this application can greatly improve power density. We have other programs under way to develop special components for automotive fuel cell systems.



50-kW (net) PEM fuel cell brassboard system.

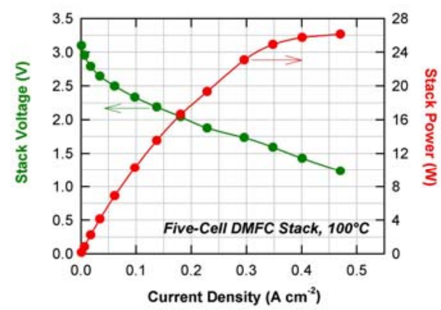
<u>Subcontractors</u>:
Honeywell-HTC, Des Plaines, IL, and Morristown, NJ
Honeywell Automotive, Southfield, MI

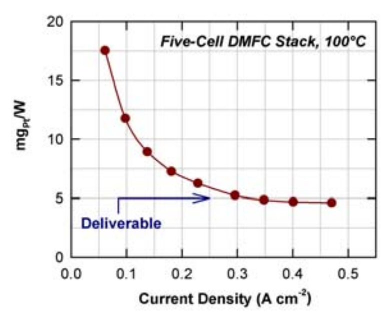
<u>Deliverable</u>: *50-kW (net) PEM fuel cell stack system (12/01).*

Direct Methanol Fuel Cells

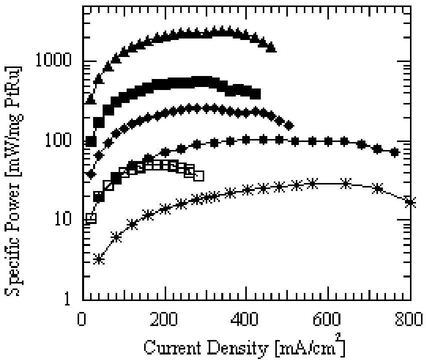
Contractor: Los Alamos National Laboratory *Los Alamos, NM*
Contact: Piotr Zelenay *(505) 667-0197*

Direct methanol fuel cell (DMFC) research at Los Alamos National Laboratory is focused on the development of materials and components, as well as optimization of cell/stack operating conditions, for potential application of DMFCs either as a main or auxiliary power source in automotive transportation. The primary goals of the research are to achieve (1) high power density, (2) high energy-conversion efficiency, and (3) low cost. Our work concentrates on lowering methanol crossover via innovative membrane and membrane-electrode assembly (MEA) research, reducing the total precious metal loading in single-cell and short-stack operation, demonstrating viability and stability of cell components in long-term operation of single cells and stacks, and designing short stacks for auxiliary power units (APUs). In particular, the research involves operation of single cells and DMFC stacks with a variety of catalysts and membrane materials to optimize performance and demonstrate stability. In addition to the fundamental fuel cell research, various cell components, such as bipolar plates, flow-fields, and gas-diffusion layers, are designed, fabricated, and tested to optimize performance of the hardware for single cells and short DMFC stacks.





<u>Deliverable</u>: *Demonstration of new membranes with 3X better selectivity in a short DMFC stack (05/02).*



Catalyst utilization curves
for sputter-deposited (▲, ■, ◆, ●),
conventional carbon-supported (□), and
-unsupported (*) PtRu catalysts.
Loading in mg/cm^2: ▲ - 0.03, ■ - 0.1,
◆ - 0.3, ● - 1, □ - 1, and * - 8.

Advanced Catalysts for Direct Methanol Fuel Cells

Contractor: Jet Propulsion Laboratory *Pasadena, CA*
Contact: S.R. Narayanan *(818) 354-0013*

Direct methanol fuel cells provide many benefits over H_2-air systems. However, state-of-the-art anode catalysts for direct methanol fuel cells require precious metals at high loadings that result in costs of \$100–\$150/kW. By sputter-deposition of thin-film layers of anode catalysts, we have increased catalyst utilization by a factor of 25 or more, greatly reducing the catalyst cost. The sputtering conditions for the standard equi-atomic PtRu catalyst will be optimized to realize such high catalyst utilization without reducing the power density of the membrane electrode assembly (MEA) power.

Sputter-deposition can also be used for discovery of new catalysts. Catalyst composition, oxygen composition, phase composition, porosity, and area loading can all be precisely controlled by varying the deposition parameters. Controlling these parameters will enable systematic variation of catalyst parameters to help in the discovery and understanding of new anode catalysts for direct methanol fuel cells.

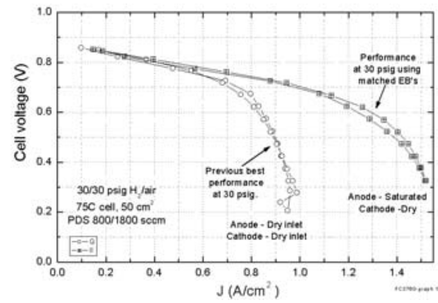
<u>Deliverable</u>: *Anode catalyst capable of achieving 2,500 mW/mg and 150 mW/cm^2 (10/02).*

PEM Stack Component Cost Reduction

High-Performance, Matching PEM Fuel Cell Components and Integrated Pilot Manufacturing Processes

Contractor: 3M — *St. Paul, MN*
Contacts: Dr. Mark K. Debe, PI — *(651) 736-9563*
Dr. Judith B. Hartmann, PM — *(651) 736-1772*

In this project, 3M is working to demonstrate a high-performance membrane electrode assembly (MEA) that has matched components, all of which can be manufactured by processes that can be scaled up to high volume production. The MEA uses a patented nanostructured thin-film catalyst and support system produced in a continuous process. The effort includes development of new anode and cathode binary catalyst compositions and structures with increased performance and stability and reduced precious metal loading, matching carbon electrode backing media that can be made by continuous processes and matching flow fields for optimized water management and gas distribution uniformity, and scaled-up pilot processes for producing each of the MEA components. The figure shows the improvement in pressurized air performance achieved by matching the electrode backings for better water management with the thin-layer catalyst. Other examples include demonstration of Pt_xM_y cathode catalysts with 0.1 mg/cm^2 Pt that outperform pure Pt and a new reformate-tolerant anode catalyst with Ru replaced by a nonprecious metal, which outperforms a PtRu control.



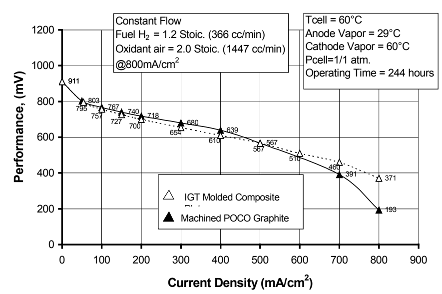
<u>Subcontractors</u>:
Phase 1: Teledyne Energy Systems, West Palm Beach, FL (formerly Energy Partners, West Palm Beach, FL); Phase 2: TBD

<u>Deliverable</u>: *~ 1-kW stack with matched components fabricated by processes consistent with high-volume manufacturing (09/02).*

Development of a $10/kW Bipolar Separator Plate

Contractor: Gas Technology Institute (GTI) — *Des Plaines, IL*
Contact: Leonard G. Marianowski — *(847) 768-0559*

A low-cost molded graphite bipolar plate that meets or surpasses DOE requirements was developed from inexpensive components. GTI-molded plates performed within 5% of state-of-the-art machined graphite plates; in fact, they operated better at high current density because of the superior hydrophilicity of the GTI-molded composite. The first stacks built with the molded plates operated in excess of 2,300 h, and plates were reused in subsequent stacks for up to 5,000 h without degradation. GTI has tested the functionality of the molded plates in cells and stacks operated at pressure, with water-cooling, and with a variety of sealant materials. Many fuel cell stacks were made with 7, 20, 52, and 70 cells and tested for endurance. The active area varied from 50 to 400 cm^2.



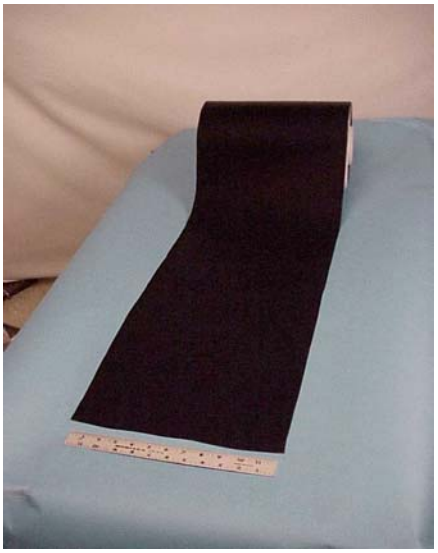
To evaluate mass production of the molding operation, GTI built and operated a 5-plate/h pilot production line. Information gained by using this pilot line will be used in the design and scale-up to commercial-scale equipment. Experience with the pilot line and various plate features has shown that some design features of the plate's flow field may not be moldable to the necessary tolerances of a multicell fuel cell stack. Also, directly molding holes and manifold slots eliminates costly post-molding machining operations.

<u>Subcontractors</u>:
Avery-Dennison-Stimsonite Corporation, Niles, IL
Superior Graphite Corporation, Chicago, IL

<u>Deliverables</u>: *Report on production and operation of molded plates (10/01) and 10-kW stack for testing at Argonne National Laboratory (10/01).*

Design and Installation of a Pilot Plant for High-Volume Electrode Production

Contractor: Southwest Research Institute *San Antonio, TX*
Contact: Dr. James Arps *(210) 522-6588*



Recent cost analyses suggest that the cost of membrane electrode assemblies (MEAs) can constitute up to 80% of the cost of a fuel cell stack. Hence, improvements in the inherent performance of MEAs, while substantially reducing the catalyst content per unit area, will contribute significantly to lowering the cost of producing fuel-cell-generated power. The development of manufacturing concepts permitting the continuous and high-speed catalyzation of electrodes should consequently decrease the cost of the MEAs and the dollars per kilowatt of power produced by the fuel cell.

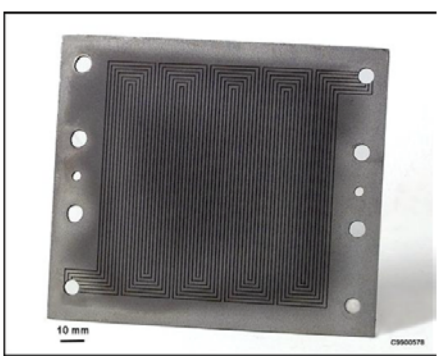
Southwest Research Institute (SwRI) is developing large-area, vacuum-based, electrode-substrate-coating technologies to reduce the overall material content of the finished part. Specifically, “ultra-low” precious-metal loaded electrodes with loadings of 0.10 mg/cm^2 or less are being fabricated by using state-of-the-art polymer electrolyte membranes and electrode substrates procured from W.L. Gore and Associates. An MEA using SwRI technology and a loading of 0.05 mg Pt/cm^2 per electrode exhibited better performance over the entire operating voltage range than a standard “baseline” MEA having a nominal loading of 0.1 mg Pt/cm^2 per electrode. The best-performing MEAs will be delivered to General Motors (Global Alternative Propulsion Center) so that it can build and supply a 50-kW fuel cell stack to Argonne National Laboratory.

Subcontractors:
General Motors, Warren, MI
W.L. Gore and Associates, Elkton, MD

Deliverable: *50-kW stack utilizing MEAs that incorporate high-volume, low-loading electrode technology (09/02).*

Carbon Composite Bipolar Plates

Contractor: Oak Ridge National Laboratory *Oak Ridge, TN*
Contact: Ted Besmann *(865) 574-6852*

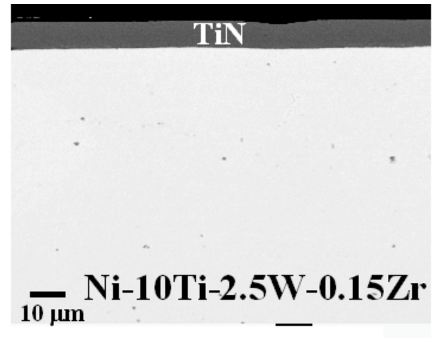


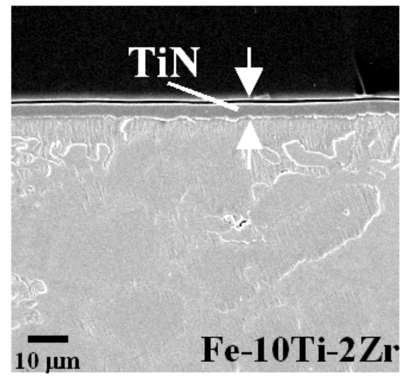
The bipolar plate is a key component of polymer electrolyte membrane (PEM) fuel cells. The reference design of high-density graphite with machined flow channels is cost-prohibitive (~$10/plate), and this problem has led to substantial R&D efforts to replace machined graphite. The requirements include low-cost materials and processing, light weight, thin (<3 mm) cross section, mechanical integrity, high electronic conductivity, low permeability (boundary between fuel and oxidant), and corrosion resistance. The approach we have developed uses a low-cost slurry-molding process to produce a carbon-fiber preform. The bipolar plate is made hermetic through chemical vapor infiltration with carbon. The infiltrated carbon also serves to make the component highly conductive. A bipolar plate (100 cm^2) we prepared was tested in a fuel cell at Los Alamos National Laboratory. The plate performed well, although further development may be needed to improve edge sealing. Surface electrical resistivity measurements of 12 Ω/cm were made, which compare favorably with the 8 Ω/cm for high-density graphite. The corrosion rate was markedly lower than even that of graphite. A preliminary cost analysis that has withstood the rigors of commercial assessment indicates plate costs of less than $2/unit, which meets DOE goals. The technology has been licensed to Porvair Fuel Cell Technology, and several fuel cell manufacturers are evaluating sample plates. We are proceeding in cooperation with Porvair to scale up production to the pilot-plant level and provide significant numbers of plates for evaluation.

Deliverable: *Series of bipolar plate materials/specimens that meet specific fuel cell manufacturer’s design needs (09/02).*

Metallic Bipolar Plates

Contractor: Oak Ridge National Laboratory *Oak Ridge, TN*
Contact: Mike Brady *(865) 574-5153*



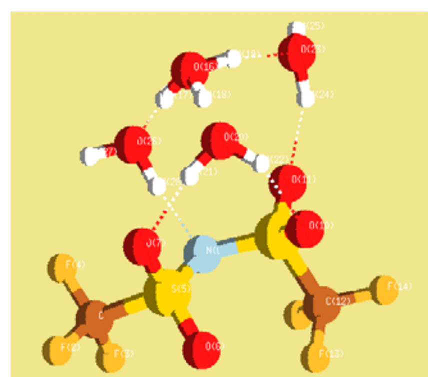


Metallic bipolar plates (<0.25 mm thickness) offer the potential for reduced weight/volume and better performance than carbon fiber and graphite plates under development. However, inadequate corrosion resistance can lead to high electrical resistance and/or contamination of the proton exchange membrane. Our goal is to develop a bipolar plate alloy that will form a conductive and corrosion-resistant TiN-based surface layer during thermal nitriding. Results to date strongly support proof of principle for this approach. A model thermally nitrided alloy (Tribocor 532N) exhibited a corrosion current density of only 6.1×10^{-7} A/cm^2 at 0.98 V vs. normal hydrogen electrode (NHE) and stable behavior for 700 h under 1 A/cm^2 in the Los Alamos National Laboratory (LANL) corrosion test cell. Essentially, no Nafion® membrane contamination was observed after a 300-h immersion in pH 2 and pH 6 sulfuric acid at 80°C. The key challenge is whether conductive and corrosion-resistant nitride zones can be produced from an alloy sufficiently ductile to permit stamping and sufficiently inexpensive to meet DOE cost goals (<$1–2 for a 500 cm^2 plate). Efforts are focused on the development of Ni-(5-15)Ti and Fe-(5-15)Ti wt.% base alloys that can meet the cost goals. These alloys exhibited a bulk electrical conductivity of ~1.5×10^4 Ω^{-1}cm^{-1} after nitriding, surpassing the DOE target by two orders of magnitude. However, corrosion testing at LANL indicated insufficient corrosion resistance in the first generation of these alloys. Process and alloy optimization is being pursued to eliminate this problem. Alternative nitriding approaches, such as high-density infrared processing, are also under investigation.

<u>Deliverable</u>: *Nitrided alloy with corrosion resistance of at least 1×10^{-6} A/cm^2 at 0.98 V vs. NHE in pH 3 sulfuric acid at 80°C, an alloy cost of less than $10/lb, and sufficient ductility to permit stamping (09/02).*

High-Temperature Membranes

Contractor: Los Alamos National Laboratory *Los Alamos, NM*
Contact: Thomas A. Zawodzinski, Jr. *(505) 667-0925*



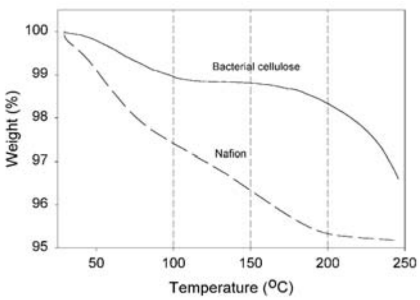
Computed structure of acid/water complex, pointing the way to new proton conductors.

The development of new polymer electrolytes for operation at elevated temperature is an important step to improved thermal management, CO tolerance, and cost for polymer electrolyte membrane fuel cells (PEMFCs). We are attacking this problem through a comprehensive effort including studies of the fundamentals of proton transport in membranes, guided synthesis of new materials, development of catalyst-coated membrane (CCM) fabrication techniques for new polymers, and coordination of university efforts aimed at synthesis of new polymers. The program has two thrusts, corresponding to short- and long-term solutions, roughly distinguished by cell operating temperature. A variety of approaches already exist to creating systems that work at 120°C. This is a short-term solution since it addresses thermal-management issues but not the CO-tolerance issue. We have shown that some existing materials are unstable in long-term tests in fuel cells, even at 120°C. A more complete solution is offered by systems operating at temperatures exceeding 150°C. However, this is an ambitious and long-term target. Replacement of water, adequate stability, and high cathode activity are not trivial objectives to achieve. Fundamental work, including computational and experimental studies of new acid-functionalized materials, is useful in this effort. The first polymers geared for temperatures exceeding 100°C are emerging, and testing is showing that, although promising, there are definite shortcomings. Work continues to make viable new materials.

<u>Deliverable</u>: *Demonstrate first LANL membrane operating at T >120°C (09/02).*

Metallized Bacterial Cellulose Membranes in Fuel Cells

Contractor: Oak Ridge National Laboratory *Oak Ridge, TN*
Contact: Jonathan Woodward *(865) 575 6826*



In current polymer electrolyte membrane (PEM) fuel cell technology, perfluorosulfonic acid-based membranes have long been the standard. The most notable drawbacks of this type of membrane are their limited stability at temperatures greater than 100°C, dependence on H_2O for conduction, and relatively high cost. Operating temperatures greater than 120°C are considered necessary for catalytic efficiency and protection of the catalyst against carbon monoxide poisoning. Bacterial cellulose, which is being investigated as a possible alternative to Nafion® membranes, has the desired physical and chemical properties for PEM fuel cell technology. The hydrated material dries to a thin membrane that is resistant to re-swelling. It is thermally stable to at least 130°C and is 1.75-fold less permeable to H_2 than Nafion 117®. It is mechanically resistant to tearing and can be folded repeatedly without damage. In the context of this program, the synthesis of a bacterial cellulose membrane with ion-conducting ability is the most important goal for the overall success of the project. The main impact, at the system level, of a cellulose-based PEM fuel cell is that it will operate at temperatures ≥ 130°C, solving one of the problems associated with Nafion®-based PEM fuel cells.

<u>Deliverable</u>: *Synthesis of a bacterial cellulose-based membrane (09/03).*

Nondestructive Study of the Water Transport Mechanism inside PEM Fuel Cells

Contractor: National Institute of Standards and Technology *Gaithersburg, MD*
Contact: M. Arif *(301) 975-6303*

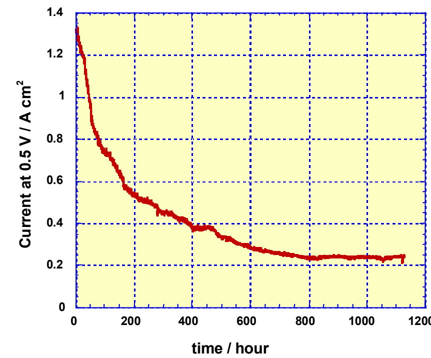
At the reactor facility of the National Institute of Standards and Technology (NIST), we are developing an advanced neutron-imaging facility and research program to study *in-situ* water transport mechanisms inside working polymer electrolyte membrane (PEM) fuel cells (and cell stacks). The goal of our research is to visualize and quantify water distribution within the gas diffusion layer (GDL) and the PEM. Near-real-time visualization of the humidification process of the GDL and the PEM and the measurements of any resulting water (or vapor) gradient are of particular interest. In addition, we will attempt to quantify the water/vapor diffusion coefficient across various interfaces within the fuel cell and study the water transport mechanism within the flow channels. We have carried out preliminary experiments with encouraging results. The new facility will be available to industries, other national laboratories, and academic institutions.

<u>Deliverables</u>: *Imaging facility for fuel cells and two-dimensional images of water distribution inside fuel cells (04/02).*

Electrodes for PEM Operation on Reformate/Air

Contractor: Los Alamos National Laboratory *Los Alamos, NM*
Contact: Thomas A. Zawodzinski Jr. *(505) 667-0925*

Performance requirements for polymer electrolyte membrane fuel cells (PEMFCs) include operation under conditions of maximum fuel-utilization efficiency and the best possible performance using gasoline-derived reformate. These requirements are tightly coupled because the former entails higher cell voltages (and thus, some focus on the PEMFC cathode), while higher operating voltages may also provide some "relief" in the context of CO tolerance. We continue to test single cells under exposure to various levels of CO, focusing on off-design conditions of the fuel processor. This work exploits the ever-increasing levels of CO tolerance we are able to achieve. Presently, by combining air injection with a specially designed anode structure using 0.4 mg/cm^2 of precious metal (PM), we can achieve tolerance to 500 ppm CO. We have demonstrated that tolerance to 100 ppm can be achieved by using as little as 0.1 mg/cm^2 of precious metal. We have also carried out testing on likely anode impurities other than CO, including ammonia and H_2S. As the targets for CO tolerance have been met or exceeded, the focus of this project has shifted to increased emphasis on achieving improved cathode performance at higher cell voltage. We seek to address these needs by developing an understanding of electrocatalysis and transport issues related to cathode performance and using this understanding to guide the development, testing, and demonstration of improved electrodes.



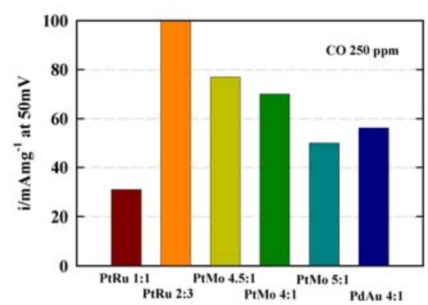
Effect of 200 ppb hydrogen sulfide in hydrogen on cell performance over time.

<u>Deliverables</u>: *Achieve 0.4 A/cm^2 @ 0.8 V on H_2 with <0.25 mg/cm^2 PM on cathode (09/02); report results on effect of H_2S on cell performance (11/01).*

Electrode Kinetics and Electrocatalysis

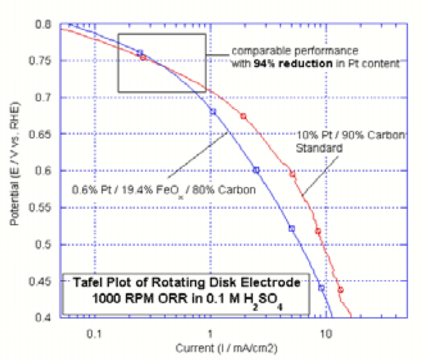
Contractor: Lawrence Berkeley National Laboratory *Berkeley, CA*
Contact: Philip N. Ross, Jr. *(510) 486-6226*

We are conducting research on the kinetics and mechanisms of the electrode reactions in polymer electrolyte membrane (PEM) fuel cells. On the basis of this research, we are developing new electrocatalysts by using a materials-by-design approach. Multimetallic catalysts are synthesized under carefully controlled conditions, producing tailor-made surfaces. Surface composition and structure are determined by using a combination of surface analytical techniques, Low Energy Electron Diffraction (LEED), Low Energy Ion Scattering (LEIS), and Auger Electron Spectroscopy (AES). Pt-Ru and Pt-Mo alloy catalysts have shown the highest level of CO-tolerance (defined as electro-oxidation of H_2 in the presence of small amounts of CO) of any Pt-based multimetallic catalyst. These catalysts operate on a bifunctional mechanism. Electronic structure calculations predict that Pd-based catalysts would show an even higher CO tolerance than Pt-based catalysts from an electronic mechanism. The first Pd-based catalyst we examined was Pd-Au, which functions entirely by an electronic mechanism; it approaches the CO tolerance of the best Pt-based catalysts. Other Pd-based multimetallic systems are under study.



<u>Deliverable</u>: *Anode catalyst with tolerance to CO levels $\geq$ 250 ppm (06/02).*

Low-Platinum and Platinum-Free Catalysts for Oxygen Reduction at Fuel Cell Cathodes

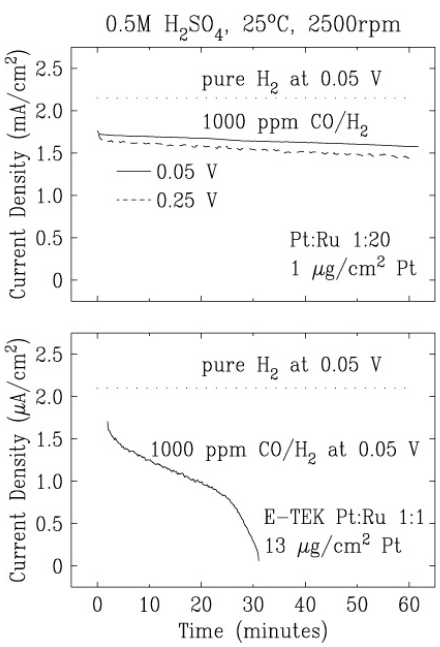


Contractor: Naval Research Laboratory *Washington, D.C.*
Contact: Karen Swider-Lyons *(202) 404-3314*

Developing advanced hydrous metal oxide catalysts designed for rapid transport of protons, water, electrons, and oxygen decreases or eliminates the precious metal content of oxygen-reduction-reaction (ORR) polymer electrolyte membrane fuel cell (PEMFC) cathode catalysts. A range of metal oxides is prepared and screened for ORR activity at the Naval Research Laboratory (Cotten, Swider-Lyons, Stanley), and leading materials are sent to Los Alamos National Laboratory for *in-situ* fuel cell testing. The structure of active materials is determined by x-ray diffraction measurements carried out at the National Synchrotron Light Source (UPenn - Dmowski, Egami). Iron, vanadium, and tin compounds show promising behavior in electrochemical half-cell measurements. Preliminary results indicate that these novel catalysts provide current densities suitable for fuel cells and yet significantly reduce precious metal content. Optimization of materials composition and synthesis and evaluation of their long-term stability are in progress.

Deliverable: *Cathode catalyst with 10x reduction in Pt (noble metal) loading (12/02).*

Low-Platinum-Loading Catalysts for Fuel Cells



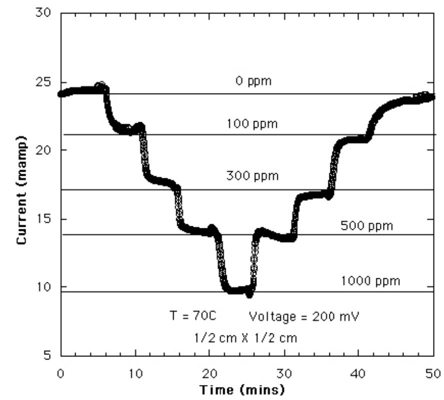
Contractor: Brookhaven National Laboratory *Upton, NY*
Contact: Radoslav Adzic *(631) 344-4522*

Our research focuses on improving the CO tolerance of Pt-Ru electrocatalysts and reducing Pt loading. Carbon monoxide (CO) tolerance can be improved and Pt loading can be reduced by using a new method to prepare Pt-Ru and similar bimetallic electrocatalysts. This new method involves the spontaneous deposition of Pt submonolayers on Ru nanoparticles, which yields electrocatalysts that have a considerably lower Pt loading and higher CO tolerance than commercial Pt-Ru alloy electrocatalysts. Spontaneous deposition may make it possible to place the Pt atoms onto the surface of Ru nanoparticles by a direct reduction of Pt ions by Ru. This atomic-level design most likely makes almost all Pt atoms available for reaction, in contrast to the Pt-Ru alloy catalysts that have Pt throughout the nanoparticles. Thus, an ultimate reduction of Pt loading can be achieved. This method also helps fine-tune the electrocatalyst's activity and selectivity by changing the coverage (cluster size) of Pt for optimal performance under required CO-tolerance levels. The results indicate that this catalyst can meet DOE's targets for Pt loadings in fuel cell anodes. The optimization of the preparatory procedure, the origin of the CO tolerance, and the activity in a membrane electrode assembly of this catalyst are being investigated.

Deliverable: *Anode catalyst with Pt-to-Ru ratio of 1:20 (06/02).*

CO Sensors for Reformate-Powered Fuel Cells

Contractor: Los Alamos National Laboratory *Los Alamos, NM*
Contact: Fernando Garzon *(505) 667-6643*

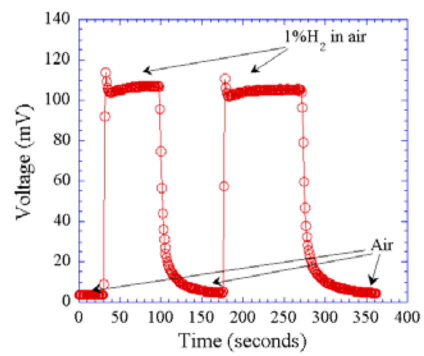


The detection and measurement of carbon monoxide in high-temperature reformate streams is of vital importance to the implementation of fuel cells for transportation. Extensive R&D is being performed to optimize low-cost fuel reformer systems that convert liquid hydrocarbon fuels to hydrogen-containing reformate to fuel polymer electrolyte membrane (PEM) fuel cells. Low concentrations of carbon monoxide (~10–100 ppm) in reformate can severely degrade the fuel cell's performance. To protect PEM fuel cells from carbon monoxide, the development of low-cost carbon monoxide sensors that provide feedback control to the fuel processing system is highly desirable. We have developed both high-temperature and low-temperature carbon monoxide sensor prototypes for use in fuel cell systems. The high-temperature sensor is a potentiometric device that operates at fuel processor temperatures. The high-temperature sensor responds well from parts-per-million (ppm) to percent levels of carbon monoxide. A perfluorosulfonic acid polymer, low-temperature carbon monoxide sensor that operates at fuel cell stack temperatures was also developed and tested under a variety of conditions, including synthetic reformate gas. The low-temperature devices respond well to carbon monoxide in hydrogen streams, as illustrated in the adjacent figure.

<u>Deliverables</u>: *Prototype carbon monoxide sensors that operate in hydrogen reformate gas streams (09/01).*

Electrochemical Sensors for PEMFC Vehicles

Contractor: Lawrence Livermore National Laboratory *Livermore, CA*
Contact: Ai-Quoc Pham *(925) 423-3394*

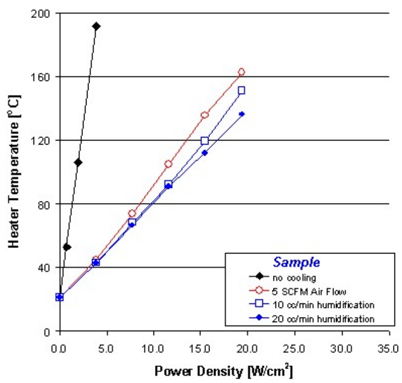


The introduction of polymer electrolyte membrane fuel cells (PEMFCs) as new transportation technology implies important changes in car design, as well as incorporation of new features not currently used in automobiles powered by the internal combustion engine. In particular, the use of hydrogen requires monitoring devices for fuel control and to ensure safety. The objective of this project is to design, develop, and demonstrate solid-state electrochemical sensors for the above applications. The sensors involve either oxygen- or proton-conducting electrolytes with active electrodes that are sensitive to hydrogen. Both potentiometric and amperometric sensors are being developed. The first potentiometric prototype exhibits a very fast response time of 1 s. The sensor is very sensitive to hydrogen in the concentration range of 0.01–1%, but it is not sensitive to humidity. Efforts to integrate the sensor on a heater are under way. An amperometric sensor is also being developed to monitor hydrogen fuel. The sensor is to be placed between the fuel reformer and the PEMFC stack to monitor the hydrogen concentration in the reformate gas. The sensor will be capable of detecting hydrogen concentrations from 1 to 100%.

<u>Deliverables</u>: *A semi-integrated hydrogen safety sensor (04/02); first prototype hydrogen fuel sensor (09/02).*

Carbon Foam for Fuel Cell Humidification

Contractor: Oak Ridge National Laboratory — *Oak Ridge, TN*
Contact: J.W. Klett — *(865) 574-5220*



The efficiency of polymer electrolyte membrane (PEM) fuel cells depends on many factors, such as humidification of the inlet air. Graphite foam has been shown to be very efficient in heat transfer with power electronic heat sinks and automotive radiators. Using the foam in the PEM fuel cell may solve problems associated with inlet air humidification. This unique graphite foam has a very high bulk-thermal conductivity. Because of its high thermal conductivity and high specific surface area, the foam can use waste heat from power electronics, cooling fluids, and exhaust gases to vaporize water on the pore surfaces efficiently and enhance humidification. The system can capture waste heat from onboard electronics, exhaust gases, cooling fluids, or other heat sources and efficiently use it to evaporate fluid into the fuel cell inlet air. Results from experiments showed that the foam can provide cooling of the electronics and supply saturated air to the fuel cell. However, one problem that will need to be addressed is balancing the heat rejection from the power electronics or the coolant with the volume of inlet air and water needed to humidify the fuel cell.

<u>Deliverables</u>: *Determine if graphite foams can be used in humidification systems (5/01); demonstrate combination of cooling of power electronics and fuel cell with humidification of the inlet air (6/01).*

Sensors for PEM Fuel Cell Reformer Flow Stream

Contractor: UTRC, UTC Fuel Cells — *South Windsor, CT*
Contact: Murdo Smith — *(860) 727-2269*

IFC-Powered Hyundai Santa Fe SUV

The objective of this effort is to develop technology and a commercial supplier base capable of supplying the physical and chemical sensors required to optimize the operation of polymer electrolyte membrane (PEM) fuel cell power plants in automotive applications. Research is conducted on candidate technologies to measure the concentration of chemical compounds in the reformed gasoline product stream for automotive PEM fuel cell power. Sensors are being developed, tested in a simulated PEM reformate environment, and then operated in a functioning laboratory prototype to determine long-term performance and durability. Sensors for physical parameters (reformate product flow rate, temperature, relative humidity, and cell stack differential pressure) are being compared to system requirements and modified as needed to meet user needs. Chemical sensor technology is being developed to detect and quantify carbon monoxide, hydrogen, sulfur compounds, ammonia, and oxygen in the hydrogen-rich reformate flow stream.

<u>Subcontractors</u>:
NexTech Materials, Ltd., Worthington, OH
ATMI, Inc., Danbury, CT
Illinois Institute of Technology, Chicago, IL

<u>Deliverables</u>: *Prototype sensors for each physical or chemical parameter will be validated and delivered to DOE for third-party testing (09/04).*

Sensor Development for PEM Fuel Cell Systems

Contractor: Honeywell Engines and Systems — *Torrance, CA*
Contact: Tony Campbell — *(310) 512-2170*

Honeywell will research and develop low-cost, reliable sensors suitable for monitoring and controlling a polymer electrolyte membrane (PEM) fuel-cell-based power plant, including the fuel cell stack, fuel reformer, and thermal-management system. The proposed program takes a system-level approach to developing the proposed sensors by leveraging Honeywell's extensive experience in PEM fuel cell systems, sensing, and controls to develop sensors that are not only low-cost and reliable, but that fully address the needs of the PEM fuel cell industry. The proposed sensors will help to improve system efficiency and safety by allowing more aggressive control strategies and more complete observation of key variables in the system.

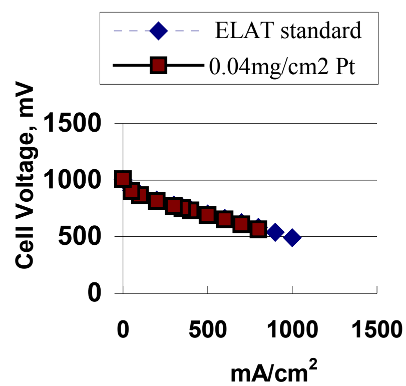
Subcontractors:
Honeywell Laboratories, Minneapolis, MN
Honeywell Sensing and Controls, Freeport, IL

Deliverables: *Prototype sensors (09/04).*

Integrated Manufacturing for Advanced MEAs

Contractor: De Nora North America, Inc. — *Somerset, NJ*
Contact: Emory S. De Castro — *(732) 545-5100*

Commercial acceptance of polymer electrolyte membrane fuel cells (PEMFCs) relies not only on competitive power density and cost, but also on efficient energy production. The first phase of this program focuses on improving cathode performance to achieve cell performance of 0.8 V at 0.4 A/cm^2 or 0.85 V at 0.1 A/cm^2 with precious metal loadings of <0.05 mg/cm^2. The approach is to develop oxygen-reduction catalysts with high metal content and to create a thin electrode structure that promotes high catalyst utilization with an optimized configuration for oxygen, proton, and water flux, thus realizing a net reduction in Pt requirements. The second phase is aimed at creating a membrane that can operate at temperatures well over 120°C. High-temperature membrane electrode assemblies (MEAs) confer several advantages, including improved tolerance to CO, enhanced cathode performance, and reduced demands for thermal management. The technical approach is to develop novel materials that support alternative proton-conduction mechanisms. The final phase involves integrating the cathode and membrane advances and creating MEAs by using pilot-scale processes. The objectives for MEA fabrication are to develop methods that are amenable to mass production, are capable of processing multiple formats, and meet the precious metal loading requirements for a commercial product. All technology verification is performed at the stack level.

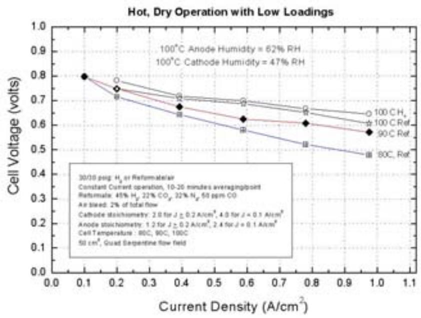


Subcontractors:
E.I. DuPont de Nemours, Wilmington, DE
Nuvera Fuel Cell, Cambridge, MA

Deliverables: *Short stack with MEAs with advanced cathodes and short stack with MEAs operating at high temperature (two stacks) (10/05).*

Advanced MEAs for Enhanced Operating Conditions

Contractor: 3M *St. Paul, MN*
Contacts: Dr. Mark K. Debe, PI *(651) 736-9563*
Dr. Judith B. Hartmann, PM *(651) 736-1772*



Baseline MEA capability.
Operation on reformate with 50 ppm CO under dry (~ 50% saturation) and hot (100°C) conditions with 0.44 mg/cm^2 of total precious metals. This new program will attempt to extend these capabilities to hotter and drier conditions and lower loadings.

This work is directed toward the development of membrane electrode assemblies (MEAs) that function under the demanding operating conditions of higher temperature and little or no humidification and that use less precious metal than current state-of-the-art MEAs. Higher-temperature operation reduces thermal management constraints — and, at sufficiently high temperatures, offers greater tolerance to fuel impurities. Operation at drier conditions offers efficiency gains associated with water and thermal management. Our experience shows that achieving these goals requires the development of MEA components that are matched to a given set of target operating conditions. Our approach will focus initially on pushing the limits of current MEA technology to permit hotter, drier operation. Our work will also include an effort to develop a polymer electrolyte membrane (PEM) that does not use water for proton transport, along with matching components to take the MEA into a new operating range of T >120°C. This effort will also include advanced catalyst development, electrode backing/gas diffusion layer and flow field optimization, an air management strategy, and process development.

Subcontractors:
TBD

Deliverable: *A full-area (250 cm^2) short stack (1–10 kW) utilizing MEAs operating under enhanced operating conditions.*

Development of High-Temperature Polymeric Membranes and Improved Cathode Structures

Contractor: UTC Fuel Cells *South Windsor, CT*
Contact: Sunita Satyapal *(860) 727-2129*

The goal of this project is to develop polymer membranes with advanced cathode catalysts capable of operating at high temperatures. Low-Pt-loading alloy cathode catalysts will be developed that have high performance at ambient pressure. For advanced fuel cells, it is desirable to combine the advantages of a solid polymer that maintains a high ionic conductivity at temperatures greater than 100°C with enhanced cathode catalytic activity. In addition to enhanced cathode catalytic activity at high temperature, advantages include improved CO tolerance; simplified water and thermal management and start-up from a frozen condition; lower electrode mass-transfer losses at high current or power densities; and a reduced heat sink and, hence, radiator size. UTC Fuel Cells has teamed with universities and research organizations to develop ionomeric membranes that operate at 120–150°C and close to ambient pressures and contain advanced Pt-alloy catalysts. The new membranes and catalysts will be fabricated into subscale and full-size membrane electrode assemblies (MEAs) and assembled and tested as a stack.

Subcontractors:
Penn State University, Princeton University, Northeastern University, Case Western Reserve University, University of South Carolina, Virginia Polytechnic Institute and State University, SRI, IONOMEM Corp., and United Technologies Research Center.

Deliverables: *Ambient-pressure PEM stack with high-temperature MEAs (120–150°C) and advanced Pt-alloy cathode catalyst (4th quarter, 2005).*

Ultra-Low Pt Cathodes through New Catalyst and Layer Structure

Contractor: Superior MicroPowders, LLC *Albuquerque, NM*
Contact: Paolina Atanassova *(505) 342-1492*

One vital area delaying the mass production of polymer electrolyte membrane fule cells (PEMFCs) is the availability of a low-cost catalyst with reproducible properties. We have developed a spray-based process for low-cost, high-volume manufacturing of high-performance, high-reproducibility electrocatalyst powders for PEMFC applications. This process serves as the platform upon which we are working to achieve the aggressive DOE low-Pt target of 1 g Pt/kW by 2005. Our goals are to significantly improve both the kinetic performance and utilization of the electrocatalyst at low-noble-metal loading in cathode layers. We will address limitations in catalyst performance through the discovery of new supported catalyst compositions and microstructures. A large variation of binary, ternary, and quaternary noble metal-transition metal alloy catalysts will be screened. We will undertake the discovery of these new catalyst formulations under conditions scaled for commercial production. The electrocatalyst formulations will be printed onto proton-conductive membranes by using digital deposition techniques. To uncover the optimum cathode layer performance, the chemical composition of the formulation and the nature of the coating will be varied. Our cathode performance target is to meet or exceed 0.5 A/cm^2 at 0.8 V in cell operation with hydrogen and 0.4 A/cm^2 at 0.8 V with reformate at a loading of ≤0.05 mg/cm^2 of precious metal in small-scale (50 cm^2), single-cell, and full-scale (250 cm^2) short stacks.

<u>Deliverable</u>: *Ultra-low platinum PEMFC air cathode structures (09/05).*

Scale-Up of Carbon/Carbon Composite Bipolar Plates

Contractor: Porvair Corporation *Hendersonville, NC*
Contact: Kenneth Butcher *(828) 693-0256*

Researchers at Oak Ridge National Laboratory have invented a technique for making bipolar plates by a carbon/carbon composite route. The technique uses a low-cost slurry molding process to produce a carbon fiber preform. The pre-form is subsequently pressed to the desired thickness and density. During the pressing operation, a flow field pattern is embossed into the surface. The pre-form is then rendered hermetic through chemical vapor infiltration with carbon. The infiltrated carbon also serves to make the component highly conductive. This process is intended to replace costly, time-consuming machining of graphite plates.

The objectives of the program are to build and demonstrate a pilot-plant facility capable of producing 300 plates/h and to demonstrate that plates made by this facility will meet or exceed all performance requirements over a period of extended use. Two iterations of the process scale-up are planned. First, a facility capable of producing about 10 parts/h will be built. Samples will be made at Porvair and tested at UTC Fuel Cells. On the basis of the results, a 300-part/h facility will be designed and built. Plates from this facility will be assembled into a 10-kW stack.

<u>Subcontractor</u>:
UTC Fuel Cells

<u>Deliverables</u>: *A production line for 300 plates/h (12/03);*
a 10-kW stack made with production plates (12/04).

Air Management Subsystems

Turbocompressor for Fuel Cell Systems

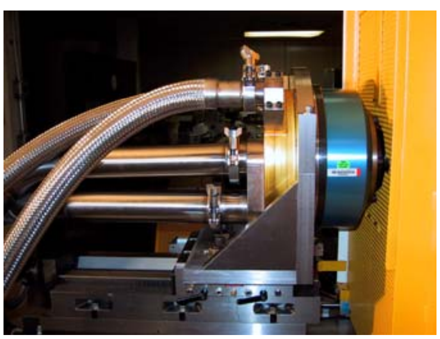
Contractor: Honeywell Engines and Systems *Torrance, CA*
Contact: Mark K. Gee *(310) 512-3606*

Fuel cell systems for transportation require a compact, lightweight, and efficient air-management system to provide a clean air flow to the fuel cell stack. Honeywell is developing a turbocompressor that meets these requirements. The turbocompressor is a motor-driven compressor/expander operating on self-sustaining compliant foil air bearings that pressurizes the fuel cell system and recovers subsequent energy from the high-pressure (and, if available, high-temperature) exhaust streams to aid in overall cell-system efficiency. Compared with positive-displacement technology, the turbocompressor offers high efficiency and low cost in a compact, lightweight package. Honeywell has improved the turbocompressor concept through three R&D phases that incorporate variable turbine nozzle and mixed-flow compressor technologies, as well as a smaller and less-expensive motor controller. In 2001, the turbocompressor was successfully operated in the Honeywell 50-kW polymer electrolyte membrane (PEM) fuel cell brassboard. The turbocompressor concept will continue to be refined, with the latest phase of development beginning in late 2001. We will continue to investigate methods of improving performance across the operating range by enhancing aerodynamics, further reducing weight and volume, and incorporating assembly methods to meet a variety of customer needs, which include concerns about short- and long-term costs.

<u>Deliverable</u>: *Turbocompressor with mixed-flow compressor, variable-geometry turbine, and motor controller (12/01).*

Innovative, High-Efficiency, Integrated Compressor/Expander Based on TIVM Geometry

Contractor: Mechanology, LLC *Attleboro, MA*
Contact: Sterling Bailey *(408) 356-5520*



TIVM Compressor/Expander Prototype Mounted on Test Stand

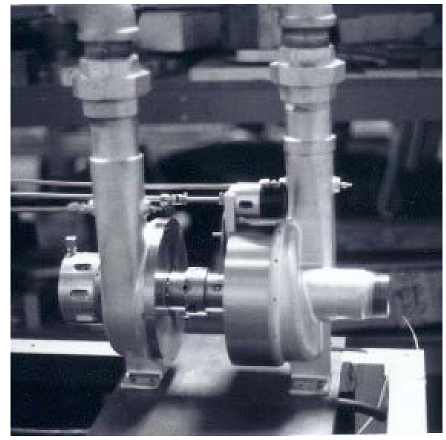
Using an efficient compressor/expander that pressurizes the air supplied to the fuel cells and recovers the energy in the pressurized exhaust gas can significantly enhance the overall performance, packaging, and cost of automotive fuel cell power systems. Adaptation of current compressor technologies has not been successful in meeting DOE performance targets. Toroidal Intersecting Vane Machine (TIVM) geometry, however, provides a new, highly innovative, continuously rotating positive-displacement integrated compressor/expander with the potential to satisfy DOE performance requirements across the operating range at an attractive package size and production cost. The basic operation of the concept and generation of pressure and flow consistent with DOE guidelines has been demonstrated with a generic prototype. Mechanology has designed and fabricated a prototype TIVM compressor/expander for a 50-kW_e automotive fuel cell system. Ongoing development is focused on improved sealing, optimization of flow porting, and qualification of materials with low friction for the meshing vane interface. A second-generation full-scale prototype will be developed and tested.

<u>Deliverable</u>: *Integrated TIVM 50-kW compressor/expander/motor prototype delivered to Argonne National Laboratory for performance testing (10/05).*

Gas-Bearing Turbocompressor

Contractor: Meruit, Inc. *Santa Monica, CA*
Contact: Pete Fonda-Bonardi *(310) 453-3259*

Turbocompressors recover stack exhaust energy to supply all or part of the air-compression requirements of a stack. The turbocompressor must be inexpensive, efficient, and oil-free and have a wide operating range. Meruit has developed a mechanically simple, very stiff leafless bearing set that will float the turbocompressor rotor at low speeds and center the rotor axially in its clearance. The bearing set is sufficiently stiff to resist the normal shocks and impacts of automotive use. The Meruit journal bearing has been demonstrated with uncoated steel bearings in uncoated steel journals and with a variety of low-friction coatings. The test program continues to improve bearing performance, demonstrate longer endurance, test coating performance, and establish trade-offs in bearing performance.



This combination of leafless journal and thrust gas bearings has been implemented with variable-geometry turbine nozzles and an optimized compressor wheel that promises a very flat operating curve. To verify system performance over the operating range, the turbocompressor test rig includes an Eaton supercharger driven by an external motor. The combination of the two compressors will meet the entire range of the DOE-specified air pressure and mass flow. The Meruit turbocompressor and its test rig have been constructed and are being calibrated.

<u>*Deliverables*</u>: *Gas-bearing, bearing test rig (10/01); turbocompressor for 50-kW turbocompressor test rig (10/01); and endurance measures of Argonne near-frictionless carbon coating (10/01).*

Motor Blower Technologies for Fuel Cell Automotive Power Systems

Contractor: UTC Fuel Cells *South Windsor, CT*
Contact: Tom Clark *(860) 727-2287*

Previous fuel cell R&D programs identified a need for advanced blower technology for near-ambient-pressure, gasoline-fueled power plants. This program is targeting development of a system consisting of a vane axial cathode air blower and two competing fuel processor blower approaches: (1) a high-speed centrifugal machine utilizing air bearings and (2) a lower-speed regenerative blower. Initial designs will strive to meet automotive efficiency, durability, weight, and volume targets. Design optimization will include a detailed cost model for high production volumes based on traditional manufacturing processes. The performance and durability of prototype units of all three blowers will be tested under conditions that simulate actual under-hood conditions. Finally, an entire air system will be integrated into a gasoline-fueled power plant to verify that all performance criteria are satisfied. To meet the objectives of this program, a variety of low-cost motor technologies will be explored, including brushless direct current (DC), synchronous induction, and switched reluctance. Ultimately, a motor technology will be selected on the basis of its performance and manufacturing cost.

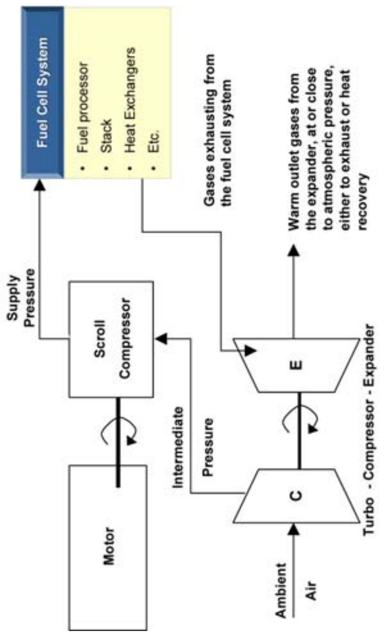
Key Capabilities	Cathode Motor-Blower		Fuel Processor Motor-Blower	
	Current	Goal	Current	Goal
Max Flow Rate (cfm)	170	170	70	70
Pressure Rise (psi)	1	1	5	12
Overall Eff. 100% Flow 25% Flow	 46 20	 60 35	 22 15	 50 30

<u>*Subcontractors:*</u>
R&D Dynamics Corporation
Phoenix Analysis & Design Technologies

<u>*Deliverables*</u>: *Cathode and fuel processor air blowers (09/03).*

Hybrid Compressor/Expander Module

Contractor: Arthur D. Little, Inc. *Cambridge, MA*
Contact: Paul McTaggart *(617) 498-5847*



Most current automotive fuel cell systems are designed for pressurized operation to reduce system size, boost stack efficiency, and improve water management. Applications for automobiles also require significant partial load capability. To meet the efficiency goals, the compressor must operate efficiently over a wide flow range, and efficient waste-energy recovery in an expander or turbine is required to offset the compression load. Traditionally, high-speed centrifugal technology has resulted in a compact package that delivers high efficiency at the design point, but performance decreases at off-design conditions. Scroll technology provides high efficiency across a broad range of operating conditions, but the resulting package is significantly larger and heavier. The objective of this program is to develop a hybrid compressor/expander module, based on both scroll and high-speed centrifugal technologies, that will combine the strengths of each technology to create a concept with superior performance at minimal size and cost. The resulting system will have efficiency and pressure delivery capability comparable with that of a scroll-only machine, at significantly reduced system size and weight when compared with scroll-only designs.

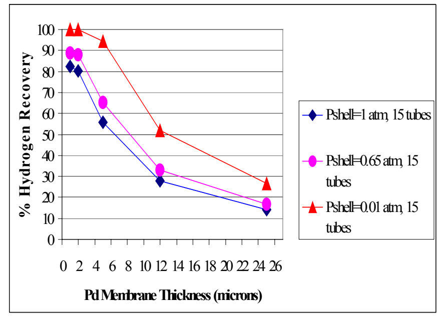
Subcontractors:
Concepts NREC, White River Junction, VT
Scroll Corporation, Carlisle, MA

Deliverable: *Hybrid compressor/expander module (08/04).*

Hydrogen Enhancement, On-Board Storage, and Refueling Technologies[4]

On-Board-Vehicle, Cost-Effective Hydrogen Enhancement Technology for Transportation PEM Fuel Cells

Contractor: United Technologies Research Center *E. Hartford, CT*
Contact: Zissis Dardas *(860) 610-7371*



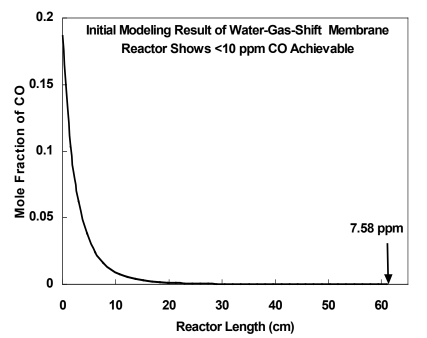
The objective of this effort is to develop an integrated Pd-based water-gas-shift (WGS) membrane reactor/hydrogen separator to produce high-purity H_2 from an integrated autothermal reformer. In Phase I, system analysis and benefits and feasibility assessments of a WGS membrane reactor integrated with balance of plant, autothermal reformer, and fuel cell stack subsystems will be performed. During Phase II, a rigorous development effort will be devoted to the synthesis and characterization of metal-supported Pd-alloy membranes. The goal is to achieve defect-free, Pd-alloy membranes with an effective thickness of <2 µm. To guide the membrane development effort, structural analysis of the membrane composite system under simulated operating conditions (thermal cycling, start-up, and shutdown) and performance evaluation in a laboratory-scale WGS membrane reactor will be used. Mathematical modeling will be used to design and simulate the performance behavior of the membrane reactor under start-up and transients. In Phase III, a 50-kW prototype membrane reactor will be built and tested with simulated reformate.

Subcontractors:
UTC Fuel Cells, South Windsor, CT
HydrogenSource, South Windsor, CT

Deliverable: *50-kW WGS membrane reactor prototype (12/30/04).*

Development of Novel WGS Membrane Reactor for H_2 Enhancement, CO Elimination, and Fuel Cells

Contractor: University of Kentucky *Lexington, KY*
Contact: W.S. Winston Ho *(859) 257-4815*



A water-gas-shift (WGS) reactor for the conversion of CO and H_2O to H_2 and CO_2 is critically needed to reduce the CO content of fuels for polymer electrolyte membrane (PEM) fuel cells. Since the WGS reaction is reversible, the reaction is inefficient. One way to significantly enhance this reaction is to use a membrane reactor, in which a membrane is used to remove CO_2 to beat the reaction equilibrium and shift the reaction toward the product side. The goal of this project is to develop a novel CO_2-selective WGS membrane reactor for H_2 enhancement via CO_2 removal and CO reduction to $\leq$10 ppm. The novel membrane reactor is based on the facilitated transport mechanism, in which CO_2 transfer through the membrane is enhanced by reaction in the membrane, and H_2 is rejected by the membrane. Initial results of modeling show that H_2 enhancement via CO_2 removal and CO reduction to $\leq$10 ppm are achievable. This three-year project is for the development of the novel reactor for a 50-kW fuel cell. In the first year, the objective is to complete the technical analysis and modeling of the novel reactor; in the second year, the objective is to demonstrate the proof of concept of the reactor by using a flat-sheet, laboratory-scale membrane; and in the third year, the objective is to complete fabrication and testing of prototype hardware of the reactor for a 50-kW fuel cell.

Deliverable: *WGS membrane reactor for a 50-kW fuel cell (09/04).*

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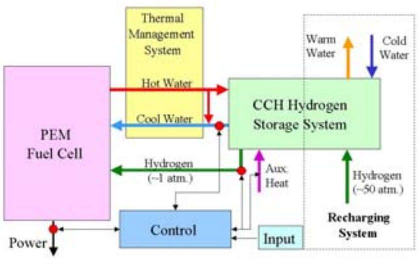
[4] These projects are co-funded by the U.S. DOE Hydrogen Program. For further information, contact Sigmund Gronich, Program Manager, U.S. Department of Energy, 1000 Independence Ave., SW, Washington, D.C. 20585. Phone: (202) 586-1623; Fax: (202) 586-5127.



High-Density Hydrogen Storage System Using $NaAlH_4$

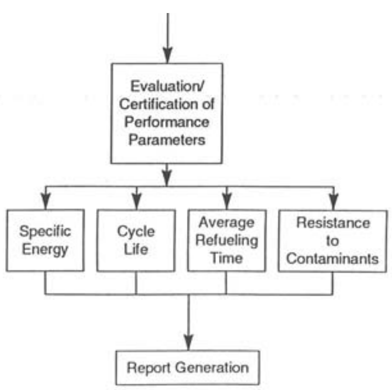
Contractor: United Technologies Research Center — *E. Hartford, CT*
Contact: Donald L. Anton — *(860) 610-7174*

The objective of this program is to develop and evaluate a hydrogen storage medium and system based on $NaAlH_4$ that has a 5-kg hydrogen capacity and can be installed in a fuel-cell-powered mid-size sedan. The system will store 6 wt% H_2 and have high volumetric (1,500 W-h/L) and gravimetric (2,000 W-h/kg) energy densities. No parasitic energy losses will be incurred during steady-state fuel cell demand. The storage medium will be cyclically regenerable for 500 charge/discharge cycles within the vehicle. Target refueling time is less than five minutes. The final targeted cost of the manufacturing system is ~$167, or $1/kW-h, assuming one-half million units are to be manufactured. Specifically, we will (1) create thermodynamic models of the $NaAlH_4$ system to determine optimum catalyzed compositional ranges; (2) cyclically evaluate selected compositions to determine degradation mechanisms and ameliorations, as well as construction materials compatibility; (3) determine safety and risk factors; (4) conduct heat and mass flow modeling to minimize volume and mass; (5) fabricate and evaluate an optimally designed hydrogen supply system in conjunction with polymer electrolyte membrane fuel cells (PEMFCs); and (6) conduct performance modeling of the combined PEMFC and hydrogen supply system under steady-state and transient conditions to establish dynamic control requirements, correlate to empirical evaluations, and establish a design database.

Deliverable: *A prototype hydrogen storage device that can be installed in a mid-size sedan with a hydrogen capacity of 5 kg (08/05).*

Standardized Testing for Chemical Hydride and Carbon Storage Technologies/Systems

Contractor: Southwest Research Institute — *San Antonio, TX*
Contact: Richard Page — *(210) 522-3252*



Likely system evaluation parameters.

Steady progress in the development of economically viable vehicular fuel-cell power-generation systems has led to a need for development of hydrogen storage systems. It appears that chemical hydride and carbon storage systems will most efficiently meet the storage capacity and safety requirements for vehicular applications. Hence, considerable effort and expense are being expended to develop chemical hydride/carbon storage systems. Southwest Research Institute will develop and operate a standardized testing system for assessing the performance, safety, and life cycle of these emergent hydrogen storage systems. The system will measure the adsorption/desorption behavior of the developmental materials. System models will be used with the results to predict the performance of full hydrogen storage systems employing the characterized materials. This facility will use standardized testing protocols that will allow DOE and the R&D organizations to assess the potential performance of the materials and systems being developed and to focus on those that show the most promise.

The project team will work with industry and the U.S. government to develop an accepted set of performance and safety evaluation standards. The presence of performance and safety standards will speed implementation once viable storage systems are developed.

Subcontractors:
Teledyne Energy Systems, Hunt Valley, MD
The National Hydrogen Association, Washington D.C.
Energy Conversion Devices, Inc., Troy, MI

Deliverables: *Standard test protocols; operational hydrogen storage test system.*

Turnkey Commercial Hydrogen Fueling Station

Contractor: Air Products and Chemicals, Inc. — *Allentown, PA*
Contact: David Guro — *(610) 481-4625*

Providing inexpensive hydrogen at a fleet operator's garage or local fueling station is a key enabling technology for direct hydrogen fuel cell vehicles (FCVs). The objective of this project is to develop a turnkey hydrogen fueling station for FCVs with state-of-the-art technology that is cost-competitive with stations dispensing hydrocarbon fuels. The major tasks of our work are to develop a cost-effective solution to the reforming of natural gas to produce a reformate stream; purify the hydrogen-rich reformate to pure hydrogen; and, finally, store, meter, and dispense hydrogen into vehicles to demonstrate a stand-alone hydrogen fueling station. We will concentrate on advanced steam-methane-reforming technologies. Sulfur-tolerant catalysts, novel heat integration techniques, and advanced materials will be investigated. Advanced adsorbent materials and novel process cycles, as well as effective integration of the two, will be investigated to obtain compact, effective hydrogen gas purification. The remaining R&D objective is to develop a commercial hydrogen dispenser meeting the needed specifications for vehicle fueling of gaseous hydrogen. Air Products will work with selected vendors to produce low-cost, user-friendly, and integrated dispensing equipment that is ergonomic, aesthetic, and safe.

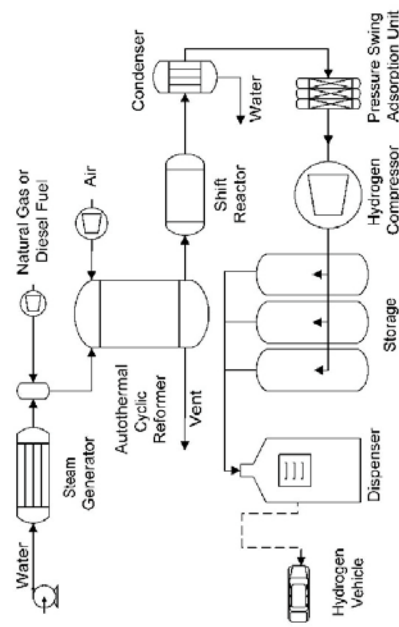
Subcontractors:
TBD

Deliverable: *Operational Fueling Station (1/01–4/04).*

Autothermal Cyclic Reformer-Based Fueling System

Contractor: GE Energy and Environmental Research Center — *Irvine, CA*
Contact: Ravi V. Kumar — *(949) 859-8851*

The technical goal of this program is to develop, design, fabricate, install, and demonstrate an Autothermal Cyclic Reforming (ACR) -based hydrogen-refueling system. The economic goal is an H_2 cost of \$2.50/kg, which is based on a natural gas price of \$3.00/MMBtu and a manufacturing rate of more than 1,000 units/year. This four-year program consists of three phases. In Phase I, the specifications for the ACR will be developed in sufficient detail to understand the competitive cost profile of the system through system analysis, conceptual design, economic analysis, and business plan development. In Phase II, the development and testing to achieve the required reliability and cost performance will be performed. Phase II includes catalyst configuration optimization, component development and testing, and detailed economic analysis. In Phase III, the H_2 refueling system will be designed, fabricated, and demonstrated.



Subcontractors:
Praxair, Danbury, CT
BP Amoco, London, England
Hydrogen Components, Inc., Littleton, CO

Deliverable: *H_2 generating and refueling system for 60 kg H_2/d (12/04).*

High-Efficiency Reformer-Based H_2 Fueling System

Contractor: Gas Technology Institute *Des Plaines, IL*
Contact: William Liss *(847) 768-0753*

A key impediment to expanded use of fuel cell vehicles is the lack of a suitable fueling infrastructure. Along with the development of an onboard liquid fuel reformer, a parallel strategy is to develop cost-competitive technology based on high-pressure, hydrogen-based fueling. This project builds on the substantial experience gained through research on compressed natural gas coupled with targeted research on the conversion of natural gas to hydrogen and innovative strategies to meet quality requirements for hydrogen fuel (in terms of water, carbon dioxide, and carbon monoxide levels). An additional core technology development is an advanced filling algorithm that will permit accurate and complete filling of compressed-hydrogen vehicles under a range of conditions. These advanced subsystems – reforming, fuel cleanup, compression, and dispensing – will be incorporated into a small, integrated, and cost-competitive fueling station capable of converting natural gas to hydrogen that will support the expansion of the hydrogen fueling infrastructure.

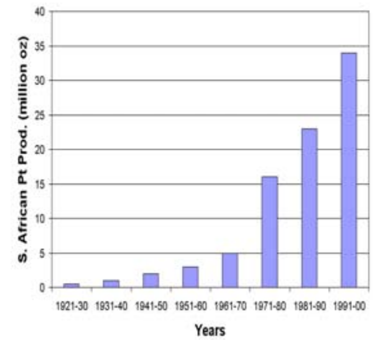
Subcontractors:
FuelMaker Corporation, Toronto, Canada
Tulsa Gas Technologies, Tulsa, OK

Deliverable: *Integrated natural-gas-to-hydrogen fuel system capable of 40–60 kg/day and fast-fill operation.*

Supporting Studies and Analysis

Precious Metal Availability and Cost Analysis for PEMFC Commercialization

Contractor: Arthur D. Little, Inc. *Cambridge, MA*
Contact: Eric J. Carlson *(617) 498-5903*

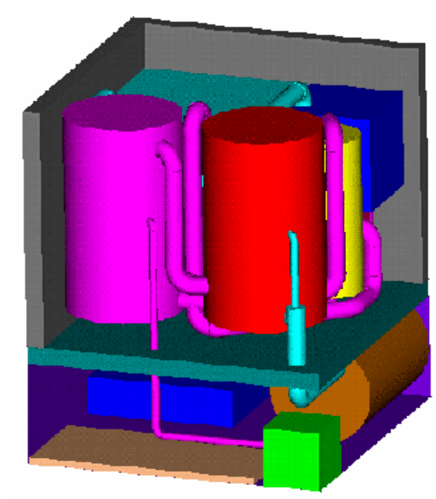


Platinum group metals (PGMs) are critical to the commercialization of fuel cells because they catalyze reforming/shift reactions in the fuel processor and electrochemical oxidation and reduction in the fuel cell. Significant penetration of fuel cells in transportation, stationary, and portable applications could create markets leading to significant pressure on PGM suppliers to increase production capacity and supply and might cause increases in PGM prices. Unless action is taken to guide the process, increases in PGM prices threaten fuel cell market viability. The overall goal of this project is not only to develop projections of PGM availability and cost, but also to identify and quantify the industry and market drivers influencing these parameters. The DOE will then have a tool with which to update PGM projections and a basis for improving the underlying model as fuel cell markets develop. An econometric model will be developed to estimate the impact of fuel cell market growth on PGM supply and pricing, including recycling of PGMs from fuel cells and the temporal and price relationships between supply capacity/reserves and long-term growth in demand for PGMs. The model will be based on experience, published data, and discussions with stakeholders.

Deliverables: *Econometric model to estimate the impact of fuel cell market growth on PGM supply and pricing; comparison of projected fuel cell and total market demand for PGMs relative to projected reserves (02/03).*

APUs for Transportation Applications

Contractor: Arthur D. Little, Inc. *Cambridge, MA*
Contact: Carole J. Read *(617) 498-6162*



Over the past years, there has been tremendous interest in the application of fuel cells for transportation applications. The focus of this interest has been on using fuel cells for propulsion power. Over the last two years, interest in using fuel cells for auxiliary power units (APUs) in vehicles has risen. Fuel cells offer many benefits for this application: decreased engine idling, higher efficiency, lower emissions, and noise reduction. The objective of this assessment is to determine the viability of polymer electrolyte membrane (PEM) and electrode-supported solid oxide fuel cells (SOFC) as APUs for on-road vehicles. Viability is defined in terms of achieving performance targets, weight and volume targets, and cost targets. For key segments of the APU/vehicle market, likely duty cycles, first cost, and weight and volume targets will be developed. System layouts and conceptual designs for up to three PEM and/or SOFC APU systems will then be developed. The most promising systems will be compared with competing approaches (e.g., internal combustion engines, battery APUs, and Stirling engines). The current gaps between fuel cell cost and performance and application requirements will be identified, and a timeline of R&D needs to bridge the gaps will be defined.

Deliverables: *Conceptual APU layouts and designs for up to three systems (PEM and SOFC systems) (10/02); update of analysis (10/03).*

Fuel Companies (examples)	Fuel Chain Module: Resource Production	Resource Transport	Fuel Production	Fuel Distribution	Fuel Marketing	Vehicle
Major Oil Companies (BP, Conoco, ExxonMobil)	●	●	●	●	●	
Methanol Companies (Methanex, BP)			●	●		
Natural Gas Companies (Southern California Gas)		●	NA	●	●	○
Hydrogen Companies (Shell Hydrogen, Air Liquide)	●	●	●	●	●	○
Ethanol Producers (BP, Conoco, ExxonMobil)	○	●	●			
Fuel Cell Companies (Excellsis, IFC, Nuvera)						●
Vehicle OEMs (GM, Ford, Chrysler)						●

Fuel Choice for FCVs – Stakeholder Risk Analysis

Contractor: Arthur D. Little, Inc. *Cambridge, MA*
Contact: Stephen Lasher *(617) 498 6108*

Despite considerable effort by DOE, the Partnership for a New Generation of Vehicles (PNGV) program, and others on the development of fuel cells for transportation, there is still considerable uncertainty around the fuel(s) that will be used by fuel cell vehicles (FCVs). Arthur D. Little is conducting a study for DOE's Office of Transportation Technologies (OTT) of the impacts of fuel choice for FCVs on energy use, greenhouse gas emissions, and cost. In this study, the risks associated with each choice will be assessed on the basis of extensive analysis and stakeholder input.

The overall risk involved in each of the fuel chains varies, and the risk may shift from one player in the value chain to another. For example, a gasoline-fueled option would place almost all of the risk with the vehicle OEMs, which would need to invest in R&D and in facilities required for commercial production, and they would therefore face any liability for the products. On the other hand, a direct hydrogen FCV choice would place much more risk with the fuel producers and the owners of the infrastructure, who would have to make significant up-front investments to establish the necessary infrastructure, even before appreciable numbers of vehicles are on the road. We intend to clarify this difficult choice and risk trade-off in this program, on the basis of a refinement of our analyses and stakeholder input.

<u>Deliverable</u>: *Analysis of stakeholder risks associated with each of the fuel choices vetted by industry and government (10/02).*

SAE Fuel Cell Codes and Standards Initiative

Contractor: Society of Automotive Engineers International (SAE) *Warrendale, PA*
Contact: Jane Hock *(724) 772-8583*

SAE's objective is to facilitate and accelerate the development of codes, standards, and recommended practices for fuel cell vehicles (FCVs). To achieve this objective, we have formed relationships with vehicle and fuel cell manufacturers, energy providers, government agencies, and others involved in the development of the required infrastructure and support facilities/structures. Working groups (WGs) established to prepare draft documents for SAE balloting include the *Emissions WG*, which will establish standards and test procedures for measuring emissions and fuel consumption of FCVs and allow a comparison with conventional vehicles; the *Interface WG,* which will develop standards that will be coordinated between fuel suppliers and vehicle manufacturers to ensure safe and customer-friendly delivery of fuel to FCVs; the *Performance WG,* which will develop procedures for testing the PEM fuel cell system and its major subsystems for automotive applications; the *Recyclability WG,* which will develop a guidance document that incorporates and summarizes existing recyclability-measurement techniques and identifies issues associated with end-of-life FCVs; the *Safety WG,* which will define essential design and construction, operation, emergency response, and maintenance requirements for the safe use of FCVs by the general public; and the *Terminology WG.* The Terminology WG document, which identified commonly used vehicle-applicable fuel-cell terminology and developed universally acceptable definitions for this terminology, has been balloted and approved and is in the final stages of publication.

<u>Deliverables</u>: *Remaining draft codes, standards, and recommended practices ready for SAE balloting (11/01–03/03).*

Guidebook to Non-U.S. Fuel Cell Developers and Suppliers in the Motor Vehicle Sector

Contractor: Breakthrough Technologies Institute — *Washington, DC*
Contact: Robert Rose — *(202) 785-4222*

Breakthrough Technologies Institute will produce a status report on the transportation-related fuel cell industry outside the United States on the basis of site visits, telephone interviews, and written questionnaires. The team will identify entities pursuing commercialization of fuel cells for vehicles of all weight classes and for auxiliary power units. The team will also identify suppliers of major components, which could include stacks and stack components and fuel processors, as well as suppliers of hydrogen storage units, balance-of-plant components, and system integrators. The team will classify companies according to size, products, market segment, financial resources, research and development budget, business status, commercialization plans, research focus, and technology status, which would be measured against the U.S. Department of Energy's targets and an assessment of the state of the art.

The result will be a guidebook to help policy makers and DOE program officials implement a cost-effective, forward-looking transportation fuel cell program. The document will also function as a guide to potential collaboration in research and development to reduce costs and reduce the time to market for transportation fuel cells. In addition, the guide will allow DOE to measure U.S. success against that of other countries.

Deliverable: *Guidebook publication (11/02).*

PEM Fuel Cell Power System on Ethanol

Contractor: Caterpillar, Inc. — *Peoria, IL*
Contact: Thomas Richards — *(309) 578-8597*

Caterpillar, Nuvera Fuel Cells, and Williams Bio-Energy have teamed up to develop and demonstrate an ethanol-fueled polymer electrolyte membrane (PEM) fuel cell system. Caterpillar and Nuvera will design and fabricate a 13-kW_e (net) integrated ethanol-fueled PEM fuel cell power system producing AC electrical power. Nuvera will design, build, and test a 13-kW_e (net) PEM fuel cell that uses ethanol as the fuel. The power module will consist of a fuel processor; CO cleanup; fuel cell; and air, fuel, water, and anode exhaust gas management subsystems. The module will also be capable of independent, stand-alone operation. A state-of-the-art control system will interface with the power system controller and control the fuel cell power module during start-up, steady-state operation, transient operation, and shutdown. Caterpillar will design, build, and test a power converter module that converts the power module's DC output into AC power. Caterpillar will also provide a system-level controller to ensure that all major subsystems work in harmony and provide constant power. Williams Bio-Energy will demonstrate performance and durability in a 4,000-h continuous stationary application demonstration under full load conditions at its ethanol production plant in Pekin, Illinois.

Williams Bio-Energy ethanol plant, site of the 4,000-h ethanol-fueled PEM fuel cell system demonstration.

Subcontractors:
Nuvera Fuel Cells, Inc., Cambridge, MA
Williams Bio-Energy, Pekin, IL

Deliverable: *13-kW (net) ethanol-fueled PEM fuel cell system (10/03).*

Fuel Cell Information Sources

Additional sources of information on fuel cells, other advanced power and vehicle technologies, and alternative fuels include the following:

- **U.S. Department of Energy, Energy Efficiency and Renewable Energy NETWORK**
  http://www.eren.doe.gov/transportation

- **U.S. Department of Energy, Office of Transportation Technologies Home Page**
  http://www.ott.doe.gov

- **The National Alternative Fuels Hotline (of the Alternative Fuels Data Center)**
  (800) 423-1DOE
  Fax: (202) 554-5049
  P.O. Box 70879
  Washington, D.C. 20024
  E-mail: hotline@afdc.nrel.gov
  http://www.afdc.nrel.gov

- **Office of Transportation Technologies Strategic Plan**

- **Research and Development Plan for the Office of Advanced Automotive Technologies**

- **Program Implementation Strategy for the Fuel Cells for Transportation Program, Office of Advanced Automotive Technologies**

- **FY 1998 Fuel Cells for Transportation Program: Contractor's Annual Progress Report**

- **FY 1998 Fuel Cells for Transportation Program: National Laboratory Annual Progress Report**

- **FY 1999 Fuel Cells for Transportation Program: National Laboratory Annual Progress Report**

- **FY 2000 Fuel Cells for Transportation Program: National Laboratory Annual Progress Report**

- **FY 2001 Fuel Cells for Transportation Program: National Laboratory Annual Progress Report**

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